TECHNICAL BULLETIN NO. 19

A FIELD STUDY OF FLOCCULATION AS A FACTOR IN ESTUARIAL SHOALING PROCESSES

by

R. B. Krone

June 1972

Prepared for the

Committee on Tidal Hydraulics
CORPS OF ENGINEERS, U. S. ARMY

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13. ABSTRACT

Simultaneous measurements of currents, salinities, and suspended sediment concentrations were made at locations upstream, inside, and downstream of an area of rapid shoaling in Savannah Harbor throughout a tidal cycle during each of three tide ranges to learn the importance of flocculation processes to the formation of shoals. The sampling stations were located in the zone of mixing of river and ocean waters. As shown in the data, chemical and hydraulic conditions prevail that together with an abundant supply of suspended particles provide the cohesion, frequency of collision, and time for formation necessary to form aggregations of large numbers of mineral particles. Changes of concentration at slack and concentration profiles at the strength of flow showed that particles have settling velocities much greater than those of the individual particles that comprise the shoal. Flocculation determines the settling velocities of suspended material at Savannah. The data also provide information on deposition and scour of sediment materials. Net upstream movement of sediment was enhanced by the deposition of suspended material at slack water followed by resuspension of larger amounts of material during flood flows than during ebb that resulted from larger bed shears imposed by flood flows. Sediment accumulates wherever later bed shears are insufficient to resuspend all of the material that deposits during periods near slack water. Material that is resuspended in the shoaling areas is transported through the face and upstream through the toe of the saline intrusion and is returned downstream in the less saline upper portion of the flows where hydraulic conditions facilitate aggregation. Particles settle downstream and subsequently can return upstream with flows near the bed. This recycling provides long times for flocculation and accounts for turbidity maxima observed along the axis of estuaries. Control of shoaling in such areas includes application of any means that reduces suspended sediment inflow, increases sediment outflow, or maintains sufficient bed shears to keep the sediment in motion.

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FOREWORD

Laboratory and field studies of the transportation processes in estuaries that lead to accumulation of cohesive sediments in deepened channels and mooring areas have been conducted by a number of branches of the Corps of Engineers. These studies have been part of a continuing effort to develop methods of harbor design and maintenance procedures that would reduce the continuing costs of dredging. It is now recognized that suspended sediments have important roles in the maintenance of water quality for recreation and wildlife, and these studies will provide valuable information for estuarial water-quality management.

This is the latest in a sequence of studies on flocculation of suspended sediment particles and on the importance of flocculation processes to the movement and accumulation of cohesive particulate materials in estuaries. Earlier studies by this author that include portions concerned with flocculation were the "Silt Transport Studies Utilizing Radioisotopes," 1956-60, and the "Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes," 1959-62, both for the San Francisco District; "Suspension of Cohesive Sediment by Wind-Generated Waves," 1963-64, for the Coastal Engineering Research Center; and "A Study of Rheologic Properties of Estuarial Sediments," 1961-63, for the Committee on Tidal Hydraulics. Only the first of these included field studies with observations of sediment movement in parts of an estuary. The subsequent laboratory studies have provided additional knowledge of the changing character of cohesive materials in deposits and during movement in suspension and of the processes of deposition and scour of cohesive particles. The field study reported herein was designed to

show the importance of these processes to the formation of shoals in an estuary.

Portions of this study were carried out by the South Atlantic Division Laboratory, the Savannah District, and the Waterways Experiment Station of the U. S. Army Corps of Engineers. The interest and splendid cooperation of the personnel in all of these organizations are largely responsible for the success of this study. Principals in each of these agencies were Mr. F. M. Bell of the South Atlantic Division, who was responsible for analyses of the water samples; Mr. J. W. Harris of the Savannah District and member of the Committee on Tidal Hydraulics, who organized the field crews and equipment and arranged for sampling of shoal material and fathometer surveys; Mr. H. J. Rhodes of the Waterways Experiment Station, who supervised the field measurements, collected and organized the data, and supervised the construction and testing of the bottom sensor; Mr. J. R. Compton of the WES Soils Division, who was responsible for analyses of shoal samples; Mr. H. B. Simmons of the WES Hydraulics Division and Member, CTH, who was responsible for organization and administration of the project; and Mr. J. B. Tiffany, Chairman, Committee on Tidal Hydraulics, who monitored the study during its planning and execution.

Mr. C. F. Wicker, Consultant to the Committee, Mr. H. B. Simmons, and the author planned the study; and Messrs. Wicker and Simmons reviewed the report before final reproduction.

The contributions made by all participants, and especially the detailed planning and review contributed to the study by Messrs. Wicker and Simmons, are gratefully acknowledged and sincerely appreciated.

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* Published under separate cover.

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NOTATION

a	Reference elevation above bed
A	Slope of logarithmic velocity profile
c_{salt}	Concentration of dissolved salts
C	Concentration of uniform suspended particles in an open channel
d	Water depth
E	Capture coefficient
g	Acceleration of gravity
G	RMS shearing rate, local velocity gradient
H,I,J	Frequency of collisions on a suspended particle by other particles due to differential settling, Brownian motion, or fluid shearing, respectively
k	Boltzman's constant, Karman's constant
m_d	Mass of dried particles
m_s	Mass of water-particle mix
n	Number concentration of suspended particles
P	Energy dissipated per unit volume of fluid
R_{ij}	Collision radius for i-size and j-size particles
t	Time
T	Absolute temperature
u	Temporal mean horizontal velocity at elevation z above bed
u_*	Shear velocity
V	Relative velocity of two settling particles
w	Settling velocity of suspended aggregates
z	Elevation above bed
ζ	w/ku_*
μ	Viscosity of water

ν	Kinematic viscosity
ρ	Water density
ρ_ℓ	Density of water with dissolved salts
ρ_p	Density of mineral particles
ρ_s	Density of water-particle mix
τ	Shear at elevation above bed z
τ_o	Shear on bed surface

SUMMARY

Simultaneous measurements of currents, salinities, and suspended sediment concentrations were made at locations upstream, inside, and downstream of an area of rapid shoaling in Savannah Harbor throughout a tidal cycle during each of three tide ranges to learn the importance of flocculation processes to the formation of shoals. The sampling stations were located in the zone of mixing of river and ocean waters. As shown in the data, chemical and hydraulic conditions prevail that together with an abundant supply of suspended particles provide the cohesion, frequency of collision, and time for formation necessary to form aggregations of large numbers of mineral particles. Changes of concentration at slack and concentration profiles at the strength of flow showed that particles have settling velocities much greater than those of the individual particles that comprise the shoal. Flocculation determines the settling velocities of suspended material at Savannah.

The data also provide information on deposition and scour of sediment materials. Net upstream movement of sediment was enhanced by the deposition of suspended material at slack water followed by resuspension of larger amounts of material during flood flows than during ebb that resulted from larger bed shears imposed by flood flows. Sediment accumulates wherever later bed shears are insufficient to resuspend all of the material that deposits during periods near slack water. Material that is resuspended in the shoaling areas is transported through the face and upstream through the toe of the saline intrusion and is returned downstream in the less saline upper portion of the flows where hydraulic conditions facilitate aggregation. Particles settle downstream and subsequently can return upstream with flows near the bed. This recycling provides long times for flocculation and accounts for turbidity maxima observed along the axis of estuaries.

Control of shoaling in such areas includes application of any means that reduces suspended sediment inflow, increases sediment outflow, or maintains sufficient bed shears to keep the sediment in motion.

Appendixes A, B, and C included herein present data from field studies, sketches of the bottom sensor, and data from shoal sample analyses, respectively. Appendix D, which presents velocities, salinities, and suspended solids from field measurements and samples, is published under separate cover in limited quantity. Copies are available upon request from the Recorder, Committee on Tidal Hydraulics, care of U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, P. O. Box 631, Vicksburg, Mississippi 39180.

A FIELD STUDY OF FLOCCULATION AS A FACTOR IN ESTUARIAL SHOALING PROCESSES

I. INTRODUCTION

"Salt" flocculation has been postulated for years to account for observed deposition of riverborne suspended sediments where river waters mix with ocean waters in estuaries. Simmons,[1] Schultz and Simmons,[2] Schultz and Tiffany,[3] and Simmons[4] have shown, however, that in estuaries such as the Savannah River estuary accumulations of sediment occur where landward transport of sediments by intruding sea water diminishes, i.e. near the landward limit of saline water intrusion where "river and ocean waters mix."

Harleman and Ippen[5] have further described the relation between the nodal point of fresh and saline water circulation near the bed and the formation of shoals. Deposition in this region appears from these studies to be primarily the consequence of net water movement resulting from density differences between fresh and ocean waters, which has led Meade[6,7] and others to question whether flocculation is a significant factor in estuarial shoaling processes.

There is little doubt that shoaling in this region is a more complex process than simple aggregation and settling resulting from the mixture of river and ocean waters. Maximum concentrations of suspended sediments are observed in the mixing regions with diminishing concentrations both landward and seaward of the mixing zone (Meade,[7] Postma,[8] and Schubel[9]), which is not accounted for in the simple model. Shoaling does not always occur in the mixing region, as in San Francisco Bay where it occurs in neighboring areas, which indicates that transport from the mixing zone is possible even if flocculation occurs there.

Fine sediment particles are carried in suspension for long distances by even sluggish rivers and then are deposited in the river estuary. There must be an increase in the settling velocity of such riverborne material after it enters the estuary. Only aggregation of the fine mineral and organic particles or of small aggregates suspended in the

river waters can account for an increase in their settling velocity. Laboratory studies[10,11] have shown that aggregation of estuarial sediments can occur at ocean water salinities greater than about 1 g/ℓ, and conditions that promote aggregation enhance the rate of deposition of suspended estuarial sediments from flowing water. These studies also showed that such aggregates are sufficiently strong to withstand transporting conditions.

Shoaling in the region in an estuary where river and ocean waters mix, therefore, can result from both currents near the bed that transport suspended sediment into the region from both downstream and upstream, and whose transporting capacity is diminished in the area, and from enhanced settling velocities of the transported particles resulting from their aggregation. This study is an investigation of the processes of aggregation in such a region and of the importance of aggregation to the formation of shoals. It was expected that such knowledge would lead to channel and harbor design and maintenance procedures that would reduce shoaling rates.

II. STUDY APPROACH AND PROCEDURES

The laboratory studies at the University of California[10,11] using uniform steady flow in recirculating flumes and rheological measurements indicated that flocculation could be a significant factor in estuarial shoaling. Field measurements were necessary to confirm the importance of aggregation to actual shoaling and to provide descriptions of cohesive suspended sediment behavior under variable density tidal flow conditions. Savannah Harbor was selected for this study because of these characteristics: It has simple geometry, a factor that is discussed further below. It is a typical example of a partially mixed estuary, which is the most common type found in the United States. Most of the shoaling occurs in a well-defined reach. Further, a number of field studies have been made in the Savannah estuary, and additional data will complement the existing information and contribute toward an overall description of sediment transport patterns there.

Study Location and Observations

A plan of Savannah Harbor, presented in fig. 1, shows the portion

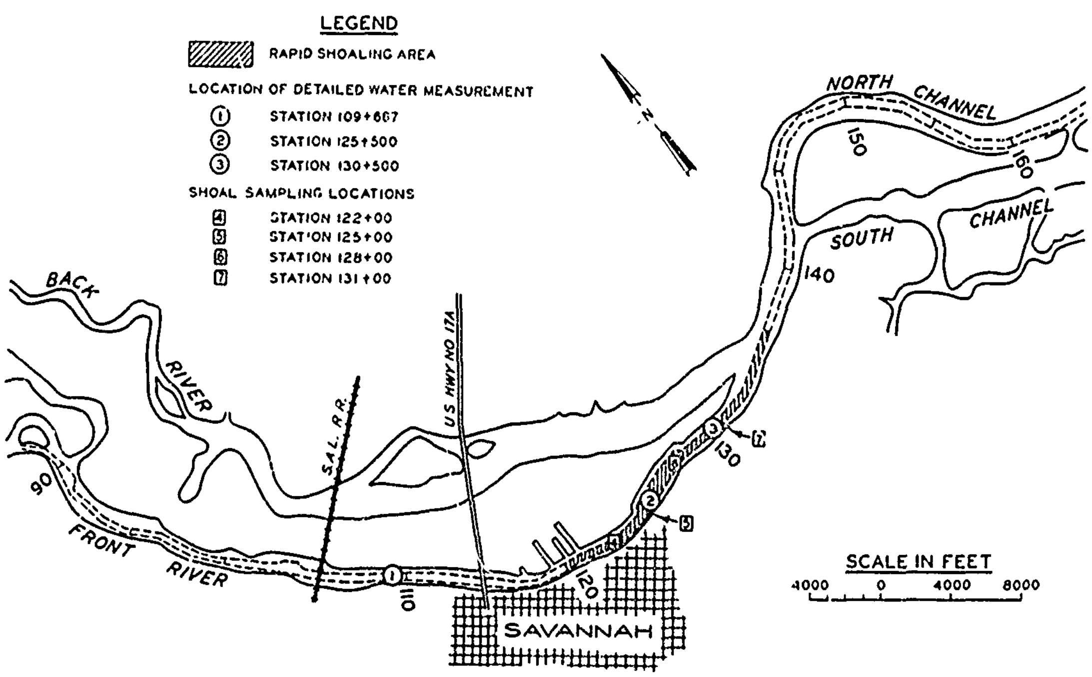


Fig. 1. Locations of water measurement and shoal sampling stations

of the channel subject to rapid shoaling and the locations of the three current measuring and water sampling stations and the four shoal sampling stations used for this study. Sampling stations were desired in uniform, straight reaches upstream and downstream from the area of rapid shoaling, and a third station was planned within the area of rapid shoaling. As shown in fig. 1, sta 109+667 and 125+500 achieved these conditions. Location of sta 130+500, however, was compromised by the junction of Back River and was located within the shoaling area at a location downstream from the area of maximum shoaling. Cross sections of the channel at the water sampling stations are shown in fig. 2.

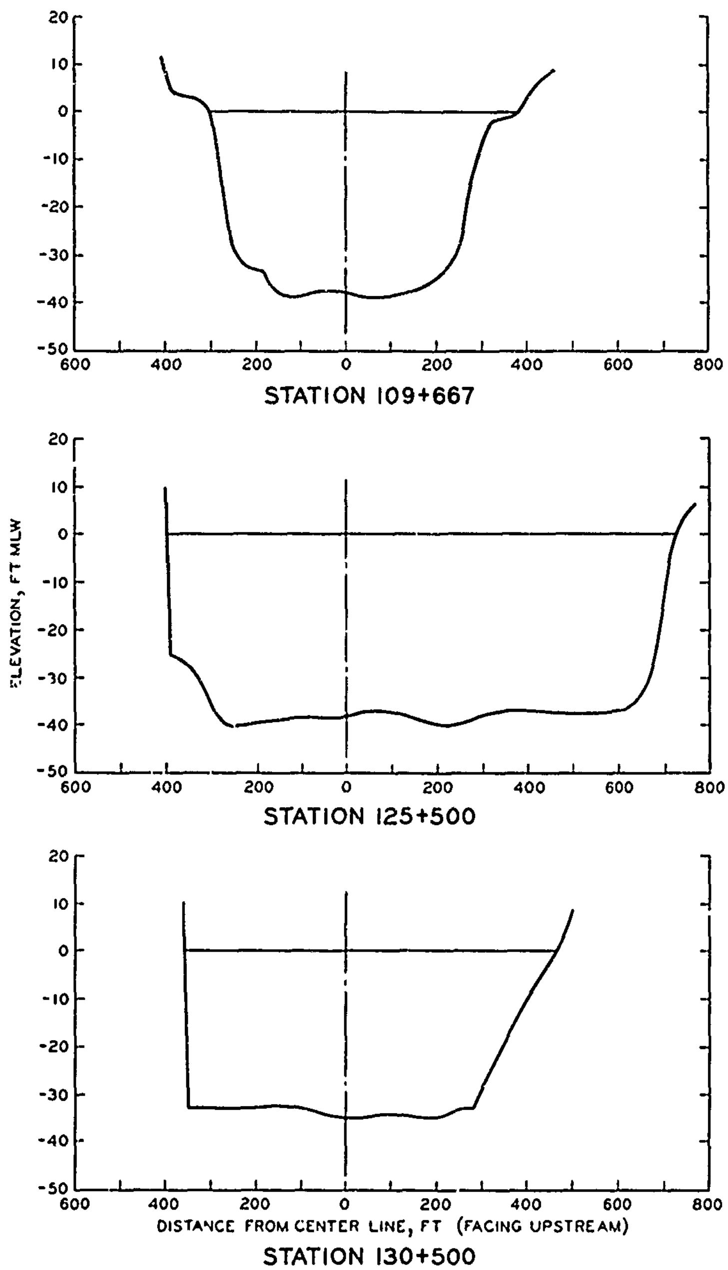


Fig. 2. Midtide cross sections at the sampling stations

Vertical distributions of suspended sediment, salinity, and currents in water entering, passing through, and leaving the shoaling area

were determined. These profiles were obtained at half-hour intervals simultaneously at each of the three stations during a complete tidal cycle. Similar sets of observations were made during a spring tide on 24 September, a mean tide on 8 October, and a neap tide on 15 October 1968. It was anticipated that these data would show directly the nature of sediment movement into the area; to what extent conditions that promote aggregation of suspended materials occur there; and during times that the velocity profile was determined by bed friction, the data should enable calculation of settling velocities of aggregates.

Freshwater inflows, winds, and tides occurring during the measurements were also determined. Samples of bed material were taken to provide descriptions of the particles, and bed surveys were made to confirm the occurrence of shoaling in the region. The dates of the field measurements and conditions that prevailed are summarized below. Environmental conditions are presented in detail in Appendix A.

Date 1968	Measurements	Tide Range ft Rise	Tide Range ft Fall	Freshwater Discharge cfs	Winds Avg mph	Winds Direction
20 Sep	Shoal samples	--	--	6930	8.6	E
24-25 Sep	Currents, suspended sediment, salinity	8.6	8.7	6650	6.0	E
1 Oct	Shoal samples	--	--	7210	5.6	SE
8 Oct	Currents, suspended sediment, salinity	7.6	7.7	6840	5.3	NW
11 Oct	Shoal samples	--	--	7050	10.9	E
15 Oct	Currents, suspended sediment, salinity	5.4	5.2	6960	11.7	NE
22 Oct	Shoal samples	--	--	7950	5.6	SE

Instrumentation and Field Procedures

Deposition of suspended materials and resuspension of deposits occur at the bed surface. The water velocities near the bed increase rapidly with distance from the bed surface. Settling of suspended matter to the bed is opposed by the combination of vertical components of turbulent flow and a concentration gradient above the bed. The shear stress on the bed, an important factor in the resuspension of deposits, is

determined by the velocity profile close to the bed. It is evident that the conditions in the water near the bed surface are important to the study, and that the elevations of the sampling points need to be accurately referenced to the bed surface.

The bed material in such regions is a soft mud. It will not support a sounding weight, and sometimes during periods of slow bottom currents it has a density so slightly greater than the water that only a ghostlike image appears on a fathometer trace. Such material is called "fluid mud" or "fluff." If such a deposit has sufficient strength to resist the shear of the water flow, however, it appears to the flow as the bed surface. For the purposes of this study the bed surface is defined as the elevation below which the current is zero when there is flow in the overlying water.

The ghost on the fathometer trace usually has a well-defined smooth upper surface. There was no assurance, however, that the upper surface was not the moving upper boundary of freshly eroded suspended sediment. Another means was needed to ascertain the elevation of the bed during each set of measurements in the profile, which led to the design for this study of a shear-strength sensitive bottom sensor. The rationale for this sensor was the observation that the shear strength necessary to resist tidal flows should be detectable and that the bed surface should be smooth and sharply defined.

Fig. 3. Bottom sensor

The bottom sensor, shown in fig. 3, consists of a 5-in.-diam hoop, or a short cylinder, 1-1/2 in. high, constructed of 0.005-in.-thick brass sheet. Three radial 0.005-in.-thick strips 1-1/2 in. high extend from a small concentric cylinder to

the hoop. When such a hoop is lowered to a sediment bed with the axis of the hoop vertical, it will settle until the total shear on the metal faces compensates the submerged weight of the hoop. The sides of three 3/4-in.-diam cylinders 2 in. long were soldered to the upper edges of the radial vanes and were filled with gasoline and water to adjust the submerged weight of the bottom sensor to 0.11 g. This sensor will respond to a bed surface that has a shear strength of 0.25 dynes/cm^2. This is well below the shear strength of aggregates of estuarial sediments measured in the laboratory.[11]

The small inner cylinder of the sensor slides freely over a short brass tube containing a magnetic reed switch. Three tiny ceramic magnets mounted at the roots of the radial vanes actuate the switch without causing appreciable friction to the movement of the sensor. An 8-in.-diam shield is provided around the sensor to reduce the effects of currents on it and to protect the sensor against physical damage. Construction sketches of the bottom sensor are included in Appendix B.

The sensor was mounted on a stiff rod 1.0 ft below a Gurley current meter. Also mounted on the rod were a 100-lb weight, an 18-in.-diam plate to reduce vertical motions from the boat, and a current direction transmitter. The instrument string is shown in fig. 4. The open end of a

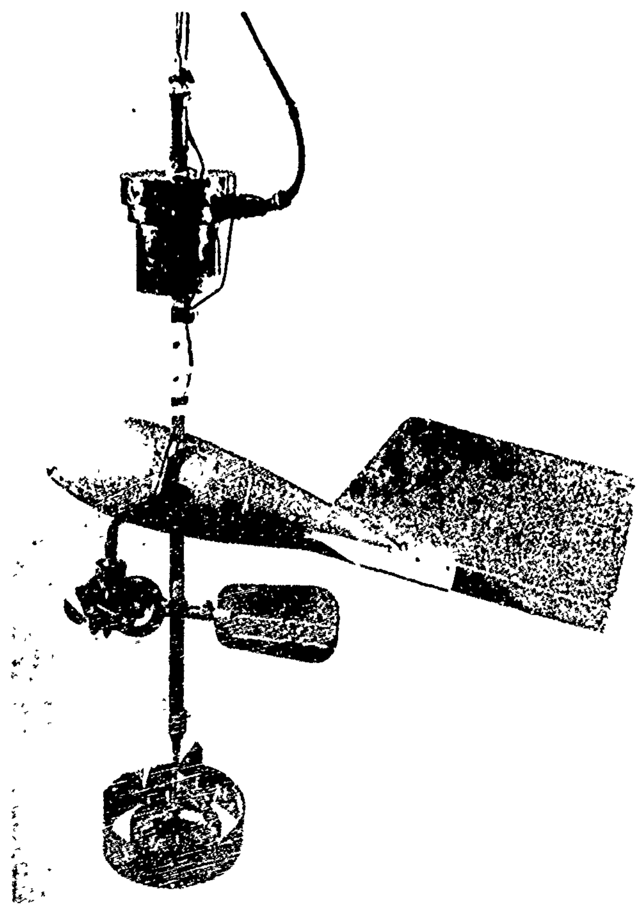


Fig. 4. Instrument string for water sampling and current measurements

3/8-in.-diam plastic tube was fastened behind the current meter and the other end was connected to an electric pump aboard the boat for sampling. The magnetic switch was connected to the Gurley current meter through a resistor and via the wire normally connected to the Gurley meter to a tone generator and earphones. The battery-operated tone generator provided a tone whenever the bottom sensor was lifted by sediment or when the current meter contacts closed.

The bottom sensor was taken to sta 125+500 at a time near slack water when a fluff surface was indicated on the fathometer trace. The bottom sensor was lowered a number of times, and the depth of the bed determined by the bottom sensor was compared with that shown by the fathometer. The agreement was always better than ± 0.2 ft, which is about as precise as the fathometer trace could be read. It can be concluded that at slack water the fluff had significant shear strength.

The measuring and sampling procedure was as follows. The instrument string was lowered to an elevation where the tone and then its absence were noted as the string was lowered and raised slightly, which indicated that the sensor was at the bed surface. The depth indicator on the instrument cable winch was then set to 1 ft, the velocity at that depth was measured, and a water sample was collected. The current meter and sampling tube intake were then raised successively to 2-, 4-, 3-, 16-, and 25-ft elevations above the bed and to 1.5 ft below the water surface, as indicated by the depth indicator; and velocities were measured and samples were collected at each depth. The sampling pump ran continuously during measurements of each current profile, and time at each elevation was allowed for the contents of the sampling tube to be displaced before collecting the sample. These measurements were made from moored skiffs.

Three to six samples of the shoal were taken at each station with a modified Trask sampler on dates shown in the tabulation on page 5. This sampler provided a 2.5-cm-diam core. The top centimeter was removed from each sample for moisture content determination. The remaining material down to a depth of 1 ft from the top of the samples from each station was composited, sealed in 1-pt jars, and sent to the WES Soils Division laboratory for analysis.

III. RESULTS OF MEASUREMENTS AND WATER ANALYSES

The sediment transportation processes depend on the character of the sediment materials, the currents, the water salinities, and the concentration of suspended sediment. It is convenient to present the analyses of shoal material first, then the results of the velocity measurements and water sample analyses together for each tide condition. The raw data from the measurements are included in Appendix C.

<u>Shoal Samples</u>

A total of 16 samples of shoal material, each of which was a composite of several samples, were submitted for analysis of physical properties. One composite was obtained at each of the four sampling stations shown in fig. 1 on 20 September, and on 1, 11, and 22 October, which bracketed the water sampling dates. Details of the physical analyses of the shoal materials are described in the "Report on Physical, Chemical, and Petrographic Data," from the WES Concrete and Soils Divisions included in Appendix C. Analyses of the physical characteristics of the samples showed no discernible patterns with respect to location or sampling date and only small variations in composition.

The average clay size particle content (less than 2 microns diameter) was 58% by weight (range 52 to 65%); most of the remainder was silt size particles, and at most a few percent of the material was fine sand. This large portion of clay size particles makes the bulk material properties largely those of the fine particles.

The mineral composition of the clays was reported to be dominantly kaolin, with minor amounts of clay-mica, montmoril[illegible], and vermiculite. Minor amounts of quartz, halite, and py[illegible]ported with smaller amounts of plagioclase, potassium feld[illegible]ssibly cristobalite. The clay minerals were poorly crystal[illegible]

The remaining physical data are summarized in the tabulation below, which was taken from the report on physical analyses, and show the small variation in physical properties. The cation exchange capacities shown are unusually high for kaolin, which might be due partially to the large amount of organic matter indicated in the last column. The presence of

relatively small amounts of montmorillonite can significantly increase the cation exchange capacity (CEC).

Field Identification Station No.	Sample No.	Specific Gravity G_s	Cation Exchange Capacity Milliequivalents/100 g Sample	Avg for Shoal	% Weight Loss on Ignition at 800 C	% Organic Content (Weight Loss at 375 C)
131 S	1	2.60	35.2	36.4	16.4	9.1
	5	2.53	39.6		16.6	
	9	2.57	32.4		15.5	
	13	2.58	38.2		n.d.*	
128 N	2	2.53	35.9	36.2	15.4	9.0
	6	n.d.	43.3		n.d.	
	10	2.58	33.5		13.9	
	14	2.62	32.0		16.4	
125 S	3	2.54	38.3	36.9	17.7	9.4
	7	2.52	30.4		15.6	
	11	2.60	40.0		15.7	
	15	2.63	38.8		n.d.	
122 N**	4	n.d.	42.3	38.9	n.d.	9.7
	8	2.53	38.0		15.1	
	12	2.56	37.6		16.3	
	16	2.53	37.6		14.8	

* Not determined.

** It is possible that sample 4 was taken on the south side of the river and samples 8, 12, and 16 were taken on the north side.

Neiheisel[12] reported the clay mineral composition of four samples taken from Savannah Harbor (SA 3, SA 4, SA 5, and SA 6). The average mineral compositions were kaolin 0.50, montmorillonite 0.44, and illite 0.06. Typical cation exchange capacities for these minerals are kaolin 3 to 15, montmorillonite 80 to 100+, and illite around 40 milliequivalents/100 g. The compositions reported by Neiheisel would have CEC values near the 36 to 39 averages shown in the tabulation above. It can be concluded that there is an appreciable amount of montmorillonite in the sediment.

The moisture contents of the top centimeter of the individual core samples before composites were made were determined to enable the calculation of bulk density of recently deposited material. The densities can be calculated according to the relation

$$\frac{1}{\rho_s} = \frac{1}{\rho_p} + \frac{m_s - m_d}{m_s} \, \frac{1 - \rho_\ell/\rho_o}{\rho_\ell - c_{salt}} \tag{1}$$

where

ρ_s = density of the suspension in grams per cubic centimeter

ρ_p = density of the particles

m_s and m_d = masses of the sample wet and dry, respectively

ρ_ℓ = density of water with dissolved salts

c_{salt} = concentration of salt in the pore fluid in grams salt per cubic centimeter of fluid

The fraction $(m_s - m_d)/m_s$ is the fraction of the sample that is evaporable water by weight. The salinity of the pore fluid in this region of changing water salinity is uncertain. Aggregates returning from the areas of higher salinity probably have pore fluid salinities like those down the estuary, depending on whether they were dispersed and reaggregated during transit. The fraction of evaporable water in the samples ranged from 0.800 to 0.887. Since it is close to one, only a small error will result by making the pore fluid the same for all, and a uniform salinity facilitates comparison. The pore fluid density was taken to be 1.025 g/cc, and the average particle density was 2.57 g/cc. The calculated densities of the average of three or more samples at each of four stations are plotted in fig. 5.

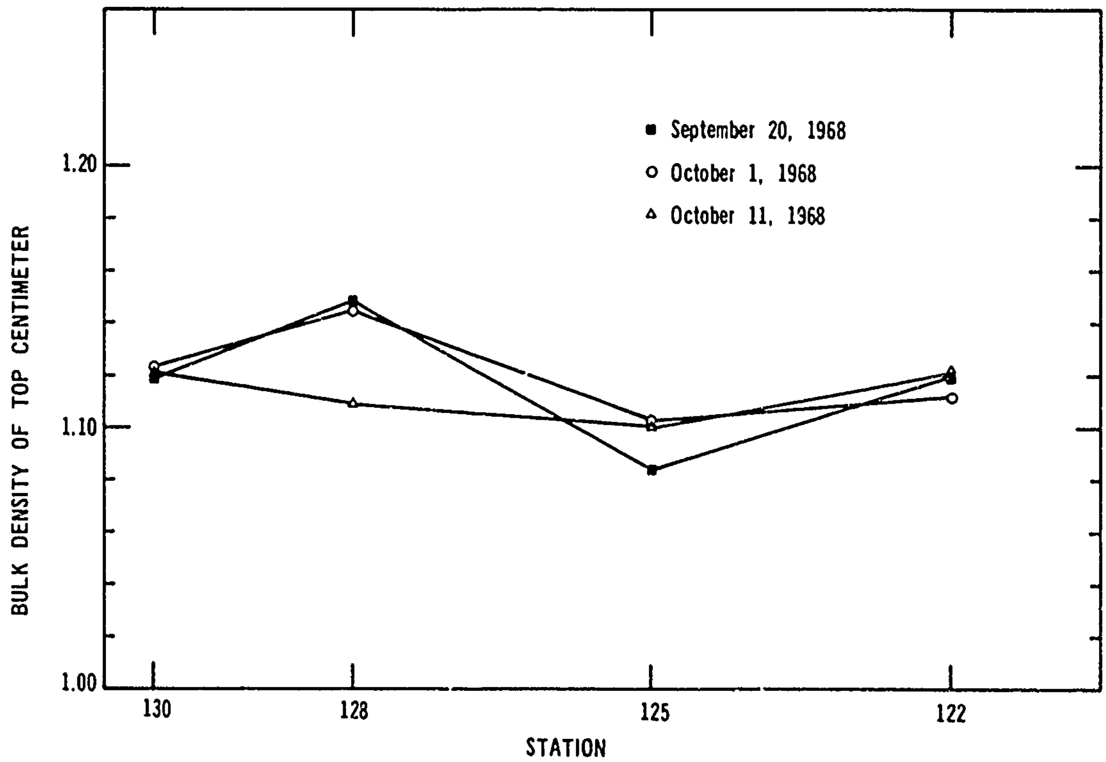


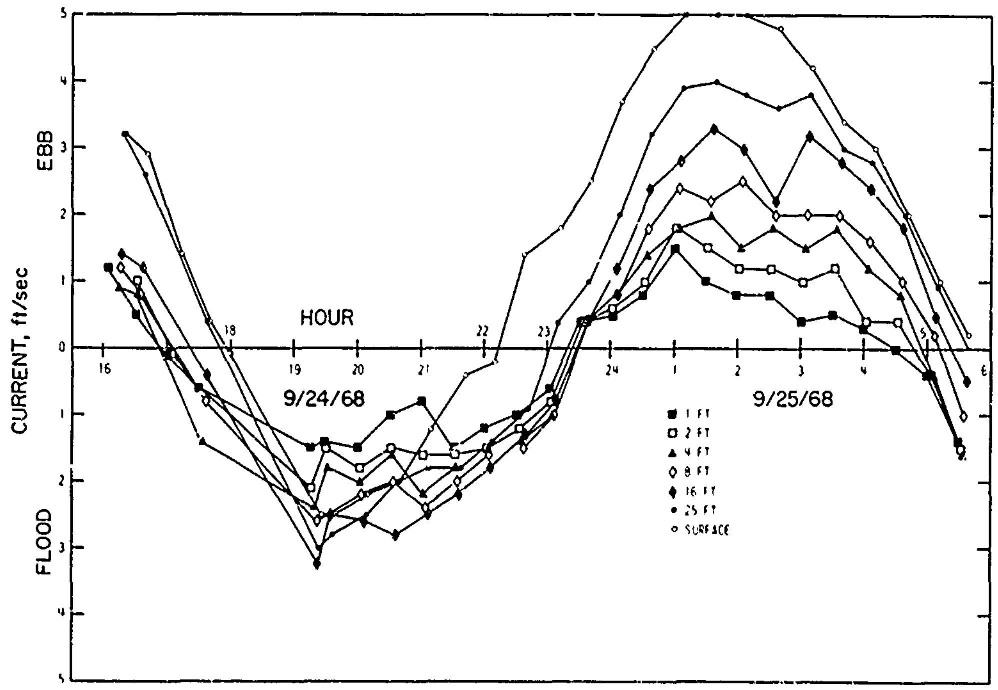
Fig. 5. Bulk densities of top centimeter of shoal

The data in fig. 5 show a slight decrease in density in the region of most rapid shoaling. The lower densities at sta 122 and 125 probably reflect shorter consolidation times on the average for sediments included in the first centimeter. The low densities of all of the samples reflect their recent deposition.

The characteristics of these sediments important to this study are the fine particle size, the large surface areas of sediment particles indicated by the significant cation exchange capacity, and the uniformity of the sediment material over the study area.

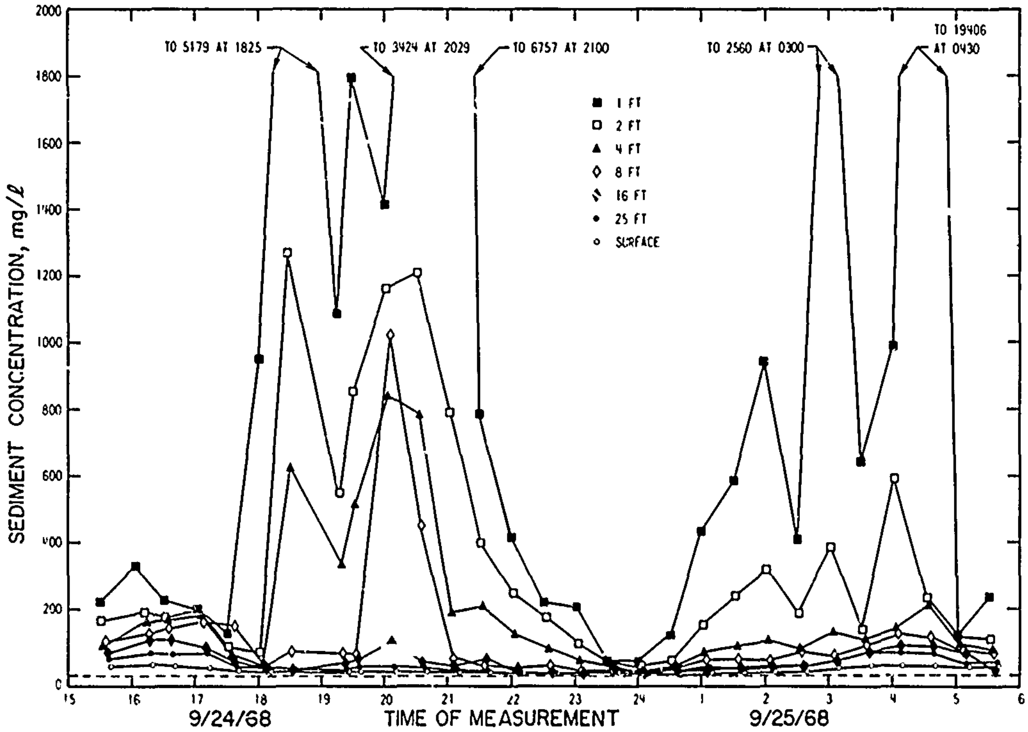
Currents, Suspended Solids, and Salinities

Measurements at Spring Tide. The data obtained from measurements made during a spring tide at sta 130+500 are presented in fig. 6. This station is located downstream from the area of maximum shoaling. The current data presented in fig. 6a show the predominantly ebb currents

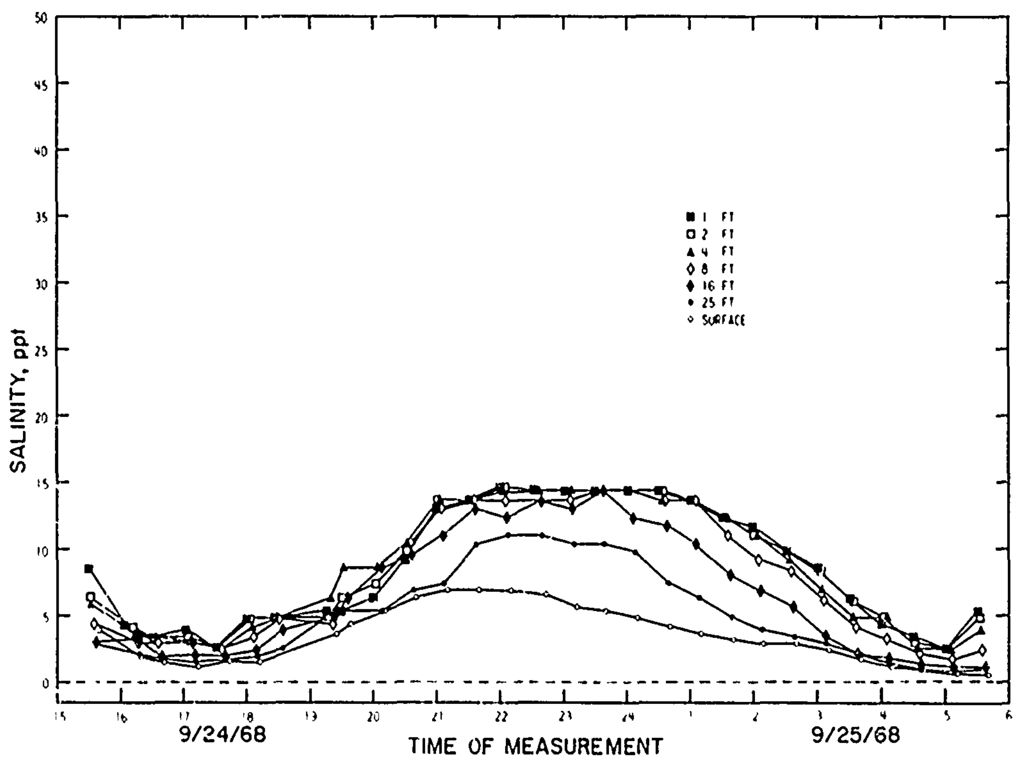


a. Currents

Fig. 6. Currents, suspended sediments, and salinities at sta 130+500 during a spring tide (Continued)



b. Suspended sediments



c. Salinities

Fig. 6. (Concluded)

near the water surface caused by the freshwater outflow overriding the sea water at lower elevations. The currents at elevations nearer the bed have slightly longer durations of flood than ebb and the flood currents are slightly stronger than those during ebb. Sediment suspended in the waters near the bed would travel a greater distance upstream than downstream.

The suspended sediment concentrations shown in fig. 6b have these striking features. The concentrations of suspended sediment in the lower 2 to 4 ft are very high during the stronger flood and ebb currents near the bed and fall to low values at times near slack water. These particles must have settling velocities much greater than those of 2-micron particles to fall to the bed so rapidly when the current is reduced. The concentration of suspended material is higher during the period of stronger flood currents than during ebb, with pronounced increases at elevations up to 8 ft. This results from the scouring of the bed to a slightly greater depth and the continued propagation upward by the turbulence of the stronger flood currents. There is an increase in suspended sediment concentration all the way to the water surface.

Comparison of figs. 6a and 6b shows also that even small variations of current near the bed have marked effects on the rate of scouring. The pronounced dip in the concentrations at times near 1930, for example, corresponds to a small dip in currents at that time. Changes in concentrations usually lag slightly behind changes in velocities because of the time required for the scouring and deposition processes.

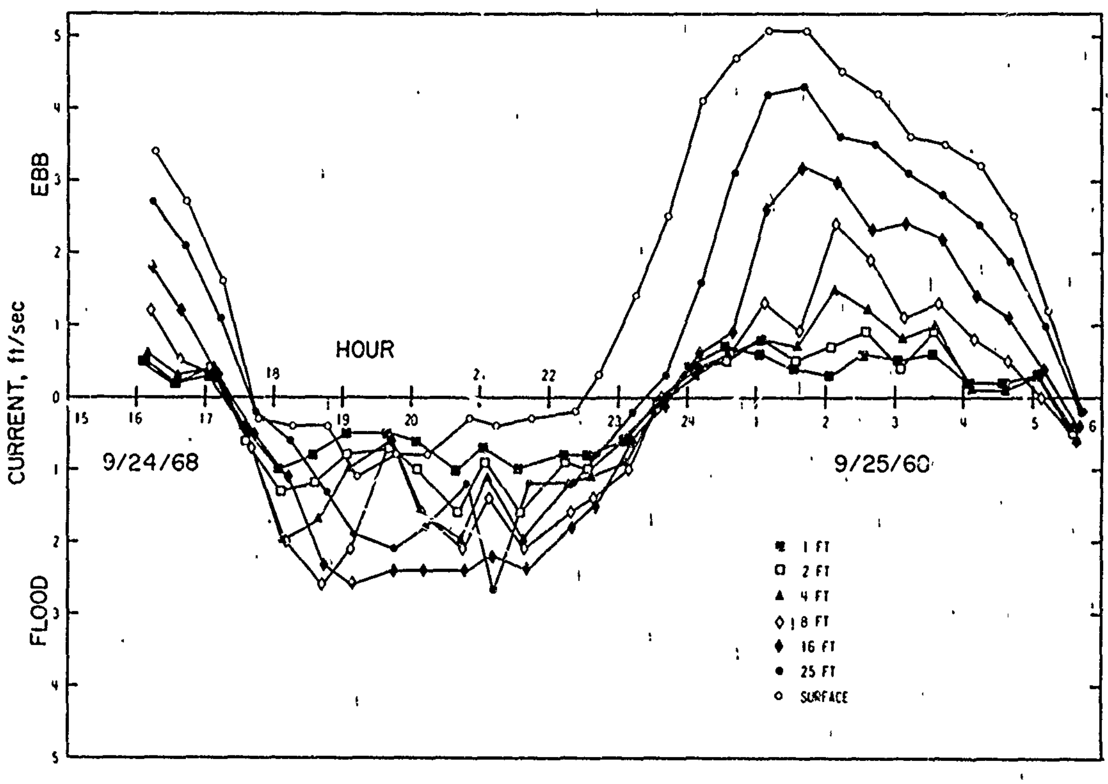
The unusually high concentration of suspended sediment shown in fig. 6b at 0430, when the indicated current at 1-ft elevation was slack, probably resulted from disturbance of the bed or from an erroneous setting of the current meter and sampling tube intake elevation. Suspension of similar material was found in the laboratory to have the characteristics of fluid mud or fluff,[10] suggesting that this sample was taken in the bottom material. The concentration at the indicated 2-ft elevation does not weakly follow the concentration at 1 ft as it does at other times, further supporting this latter interpretation.

The salinity data in fig. 6c show that higher salinities persist longer near the bed than do those near the surface. The salinities are

about 90 degrees out of phase with the currents and are significant at all depths. The appreciable salinities of the waters 25 ft above the bed and at the surface indicate that sea water intruding near the bed mixes upward with the overriding fresh water.

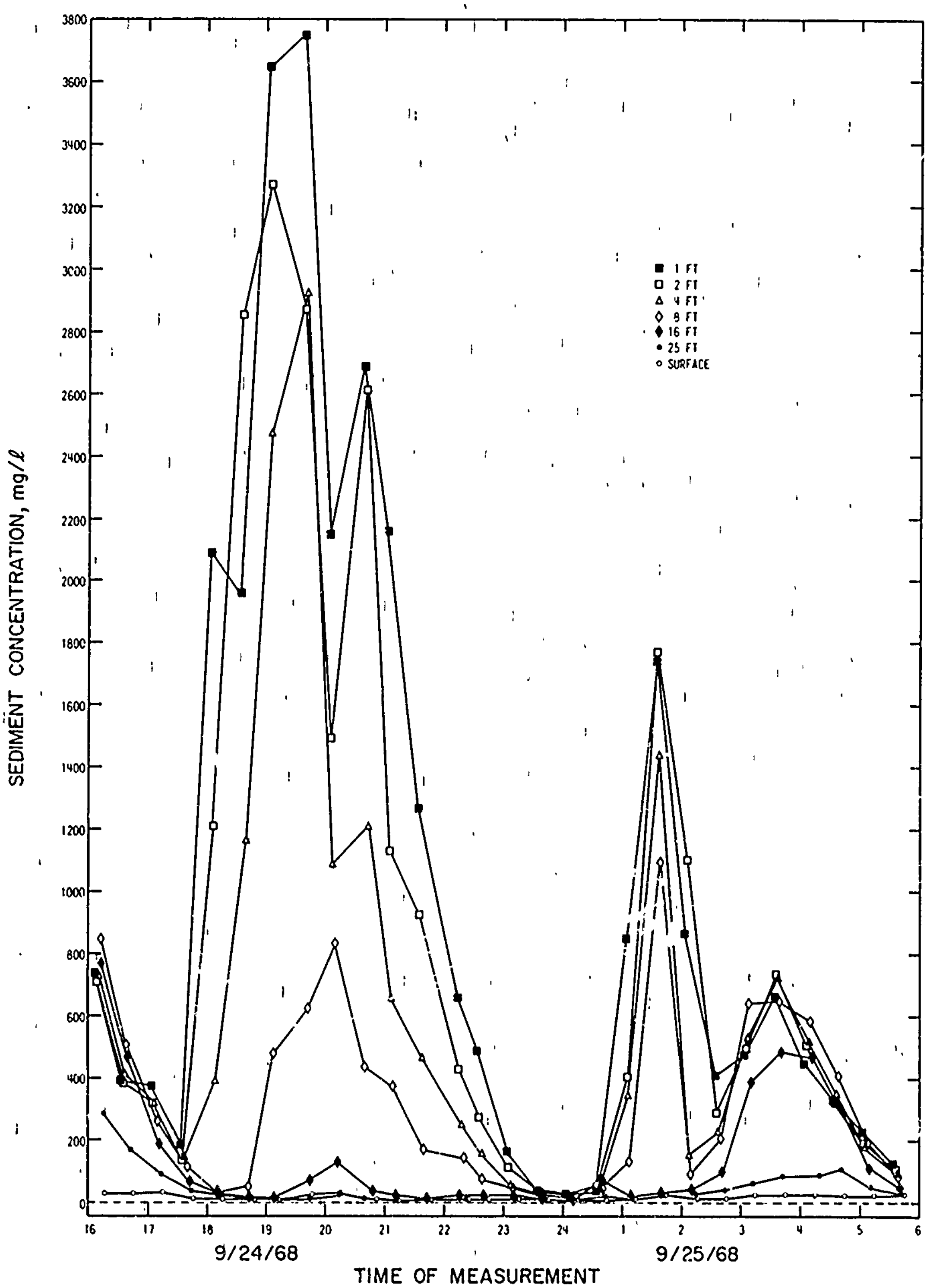
The higher concentrations of suspended sediments scoured from the bed during flood than those scoured during ebb and the greater distance of travel of floodwaters near the bed result in net upstream transport near the bed of sediment materials from sta 130+500.

The data from the measurements made at sta 125+500 during the spring tide are presented in fig. 7. Sta 125+500 is located in the area of maximum shoaling. These data show that the surface flows have a much stronger ebb predominance than those at sta 130+500, and the bottom currents persisted longer, as well as being stronger, during flood than during ebb. The bottom currents are weaker than those at sta 130+500 because of the widened channel at sta 125+500.



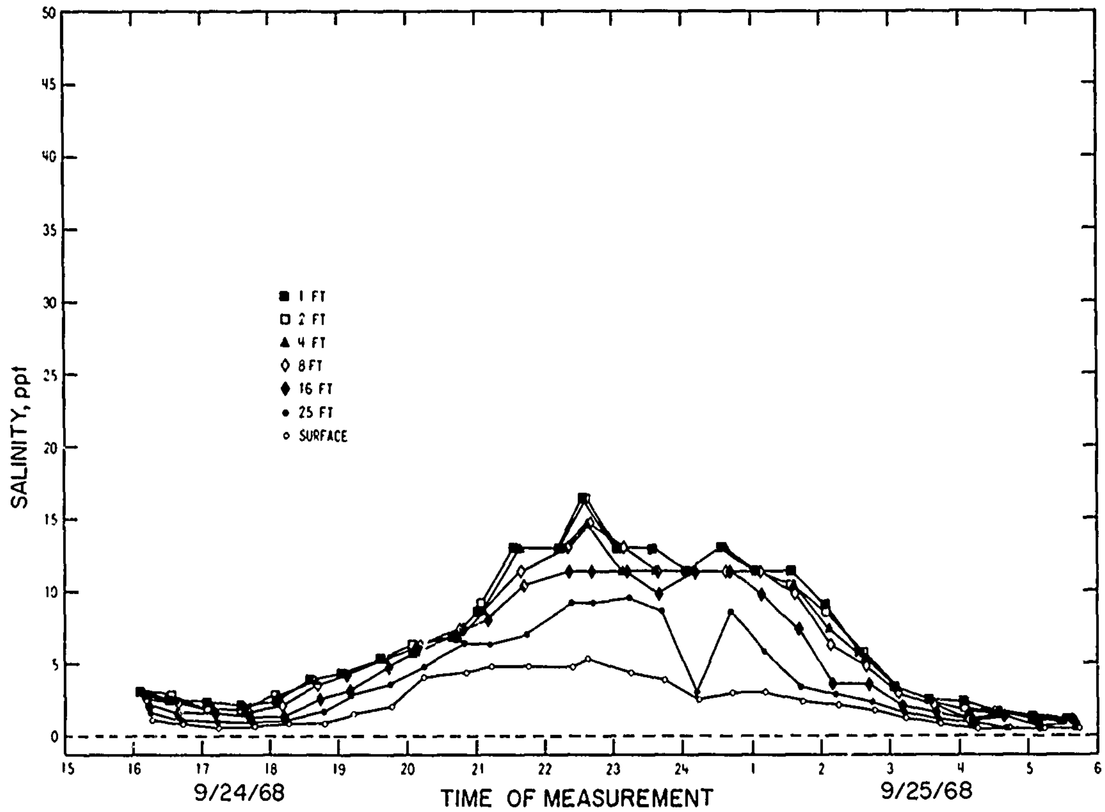
a. Currents

Fig. 7. Currents, suspended sediments, and salinities at sta 125+500 during a spring tide (Continued)



b. Suspended sediments

Fig. 7. (Continued)

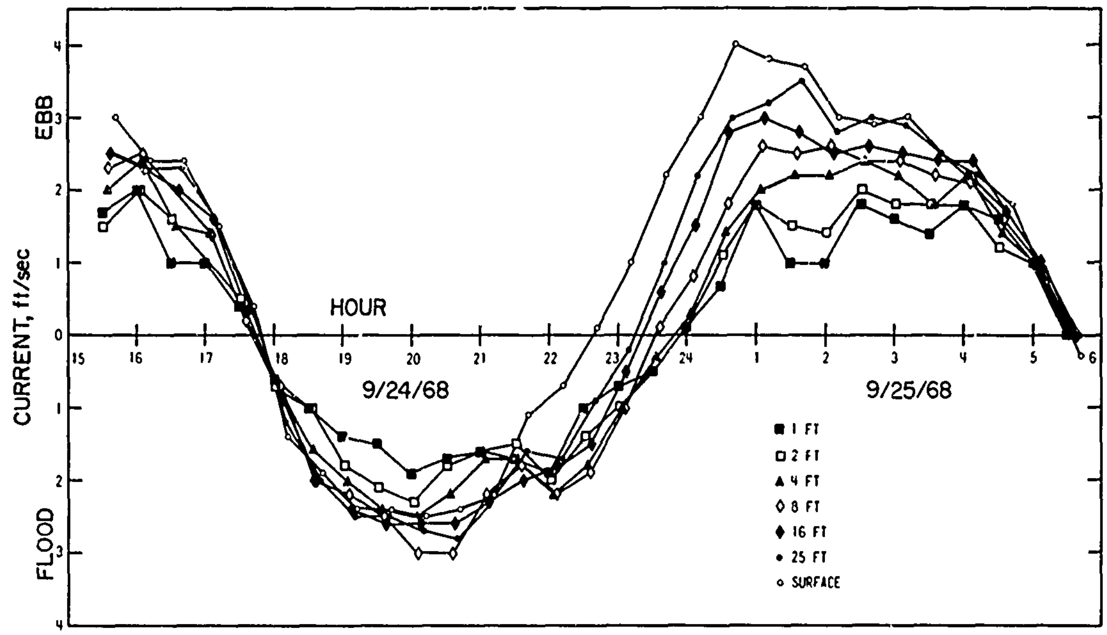


c. Salinities

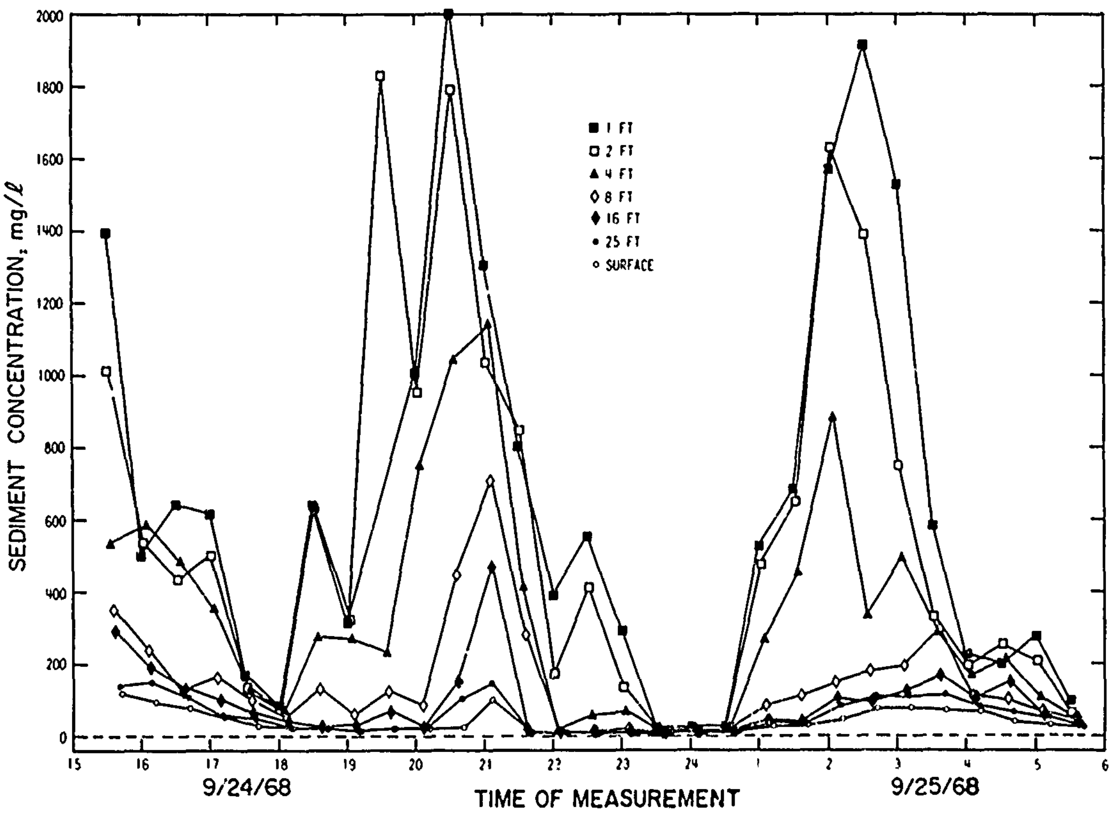
Fig. 7. (Concluded)

The suspended sediment concentrations (fig. 7b) show deposition near slack water and resuspension during the strength of bottom currents with a very marked difference between the concentrations and durations during flood and ebb. The maximum concentrations are lower than those at sta 130+500. The sensitivity of the bed surface to resuspension by small increases in current velocity is shown by the double peak in the suspended sediment concentration during ebb that resulted from the slight double maximum in 1-ft ebb currents. The reduced bottom currents caused by the channel widening reduce the competence of the flood currents for transporting sediment through this area by reducing both the the amount resuspended and the velocity of transport.

The salinities (fig. 7c) show that sta 125+500 is in the mixing zone, and that the salinities are everywhere adequate to cause cohesion of suspended clay particles.

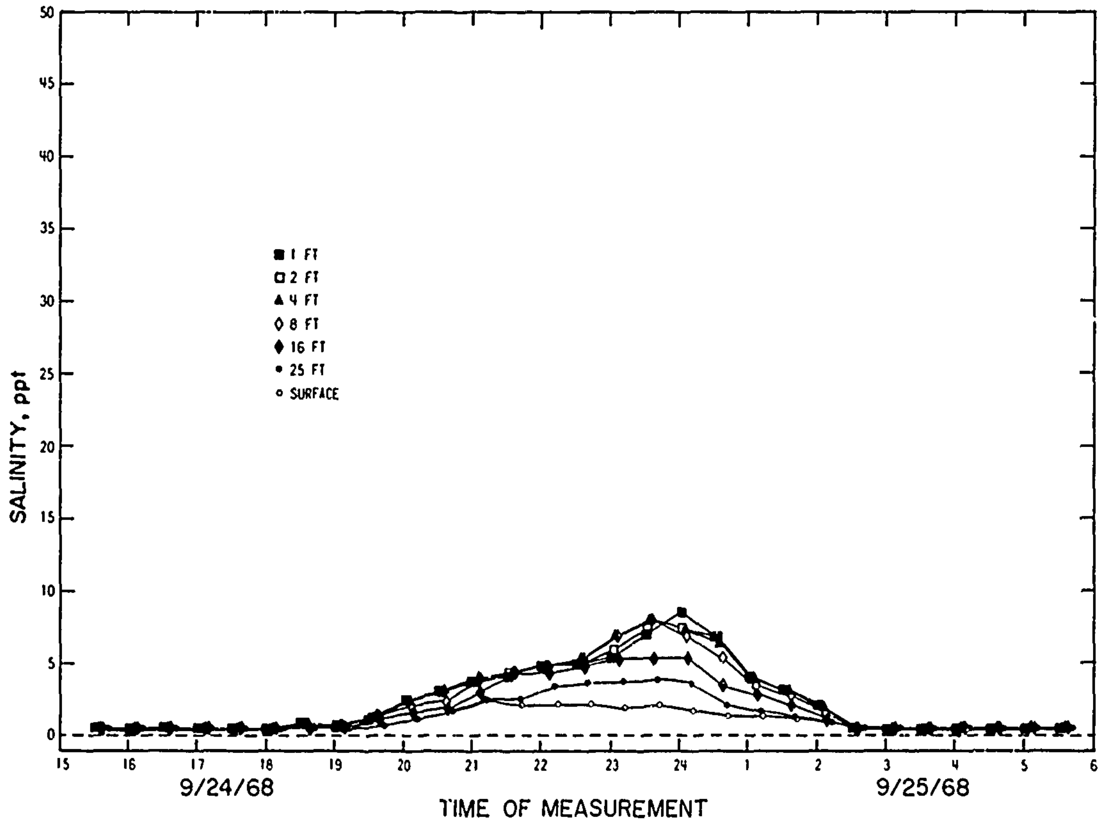


a. Currents



b. Suspended sediments

Fig. 8. Currents, suspended sediments, and salinities at sta 109+667 during a spring tide (Continued)



c. Salinities

Fig. 8 (Concluded)

Fig. 8 presents data from the measurements at sta 109+667, located upstream from the shoaling area. The current data (fig. 8a) show less ebb predominance at the surface but higher currents at the bed than those observed at sta 125+500. These higher currents result from the reduced channel width.

The suspended sediment concentrations (fig. 8b) show suspension during ebb and flood as at the other stations, with a smaller difference in the durations and concentrations. The maximum concentrations during flood at any level at sta 109+667 are lower than those observed at sta 125+500, however. Since the currents are greater, and would scour the bed to greater depths if easily erodible sediment were there, the reduced concentration must be due to the limited amount of material to be suspended. The material entering the study region at sta 130+500 was either deposited in the widened area where the transporting capacity is

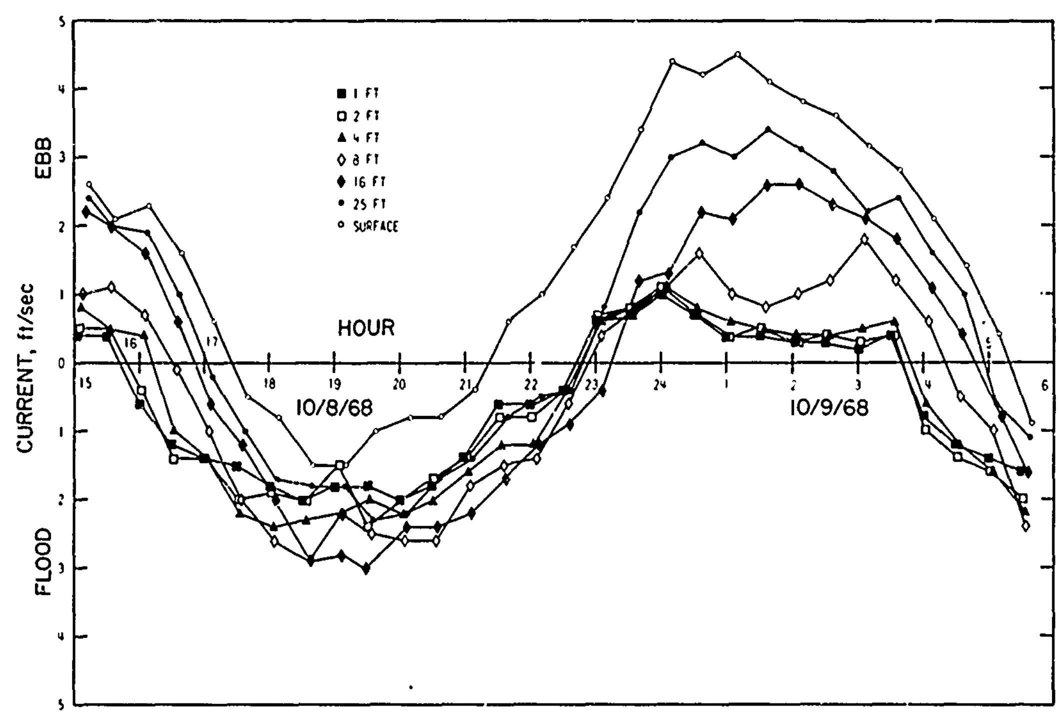
reduced or has mixed with the overlying water and was carried seaward. The absence of shoals at sta 109+667 supports this interpretation.

The suspended material settled rapidly at sta 109+667 when the currents diminished, indicating that the material was aggregated.

The salinities presented in fig. 8c show that sta 109+667 was near the average position of the upstream limit of the mixing zone during spring tide at the freshwater flow of 6600 cfs.

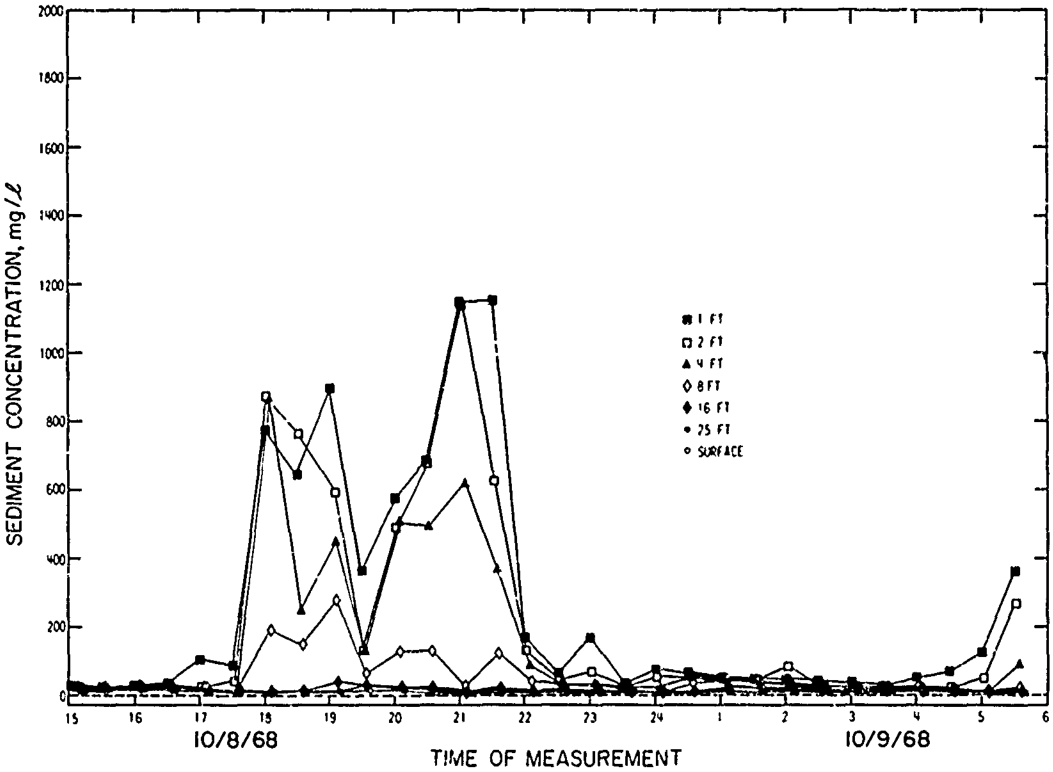
Measurements at Mean Tide. The data from the measurements made under mean tide conditions are presented in figs. 9, 10, and 11 for sta 130+500, 125+500, and 109+667, respectively. These figures show that the currents, suspended solids concentrations, and salinities are similar to those that prevailed during the spring tide measurements. Several important differences are worth noting, however.

The bottom currents at sta 130+500, presented in fig. 9, show a

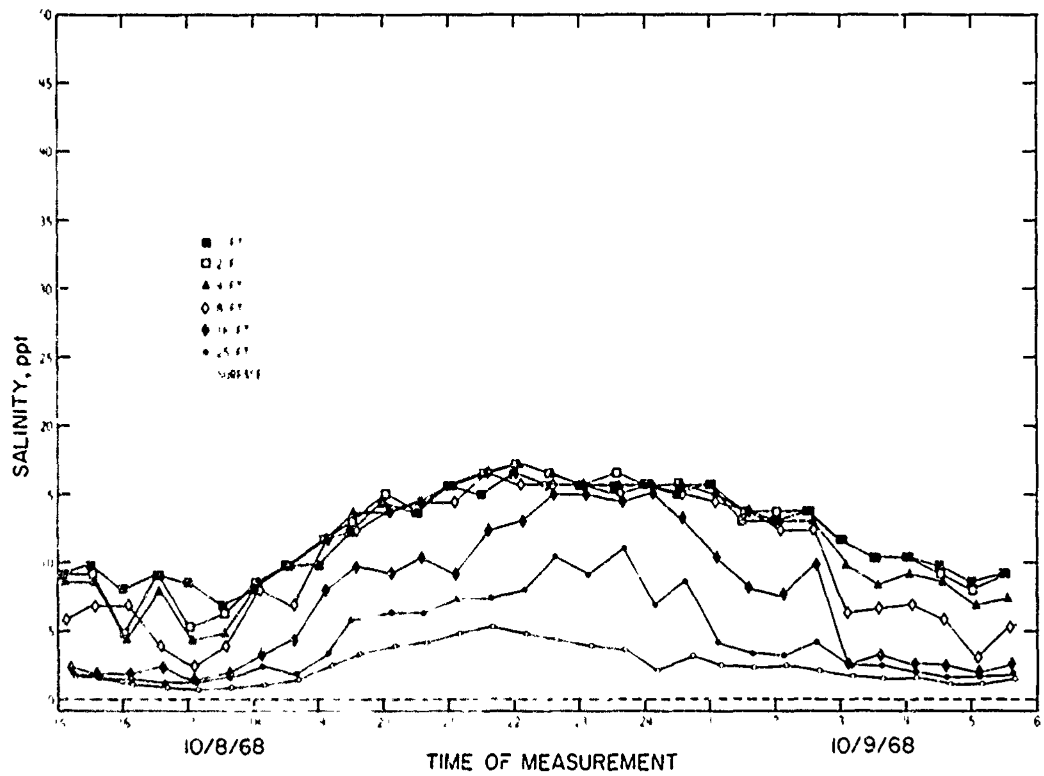


a. Currents

Fig. 9. Currents, suspended sediments, and salinities at sta 130+500 during a mean tide (Continued)

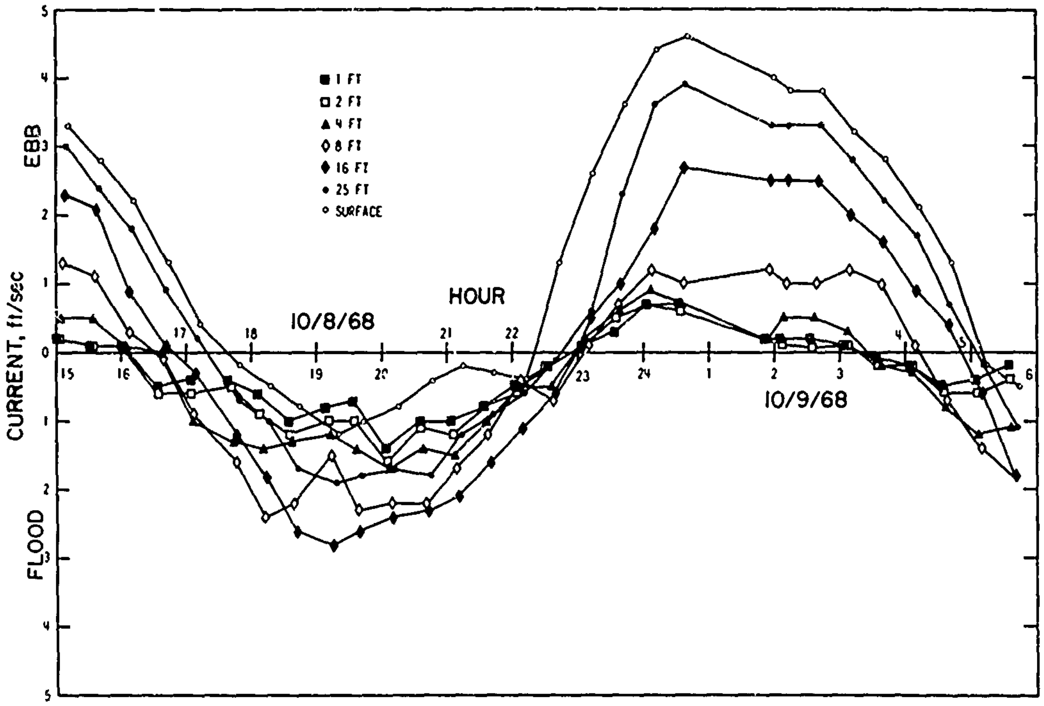


b. Suspended sediments

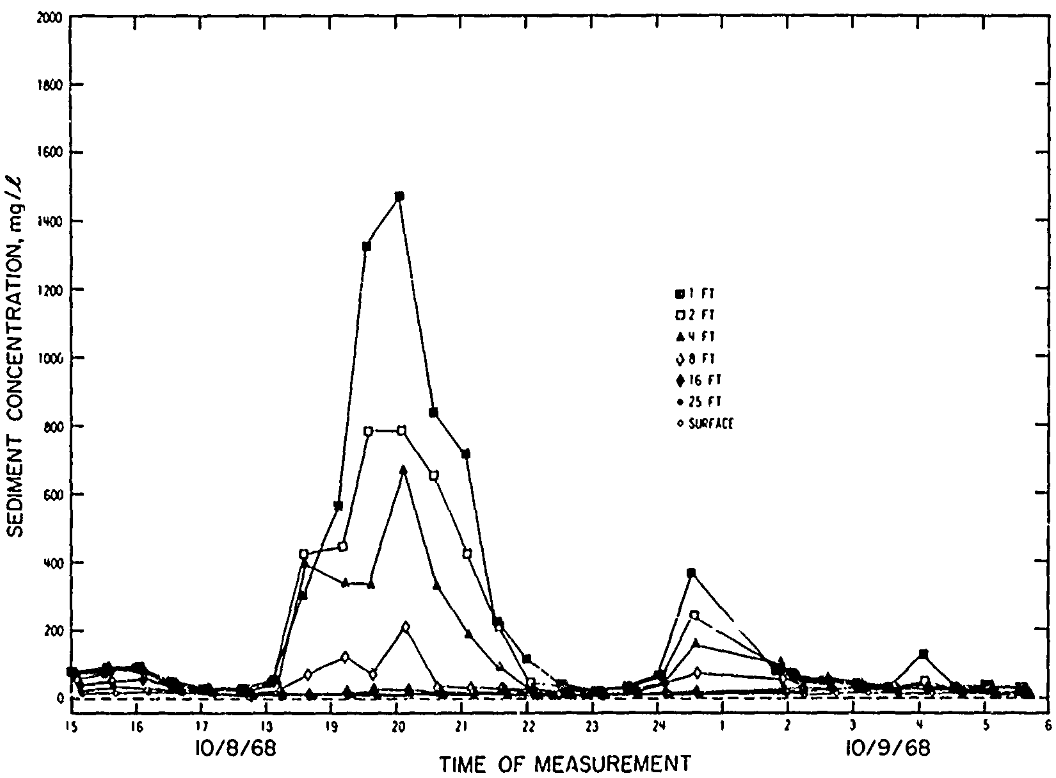


c. Salinities

Fig. 9. (Concluded)

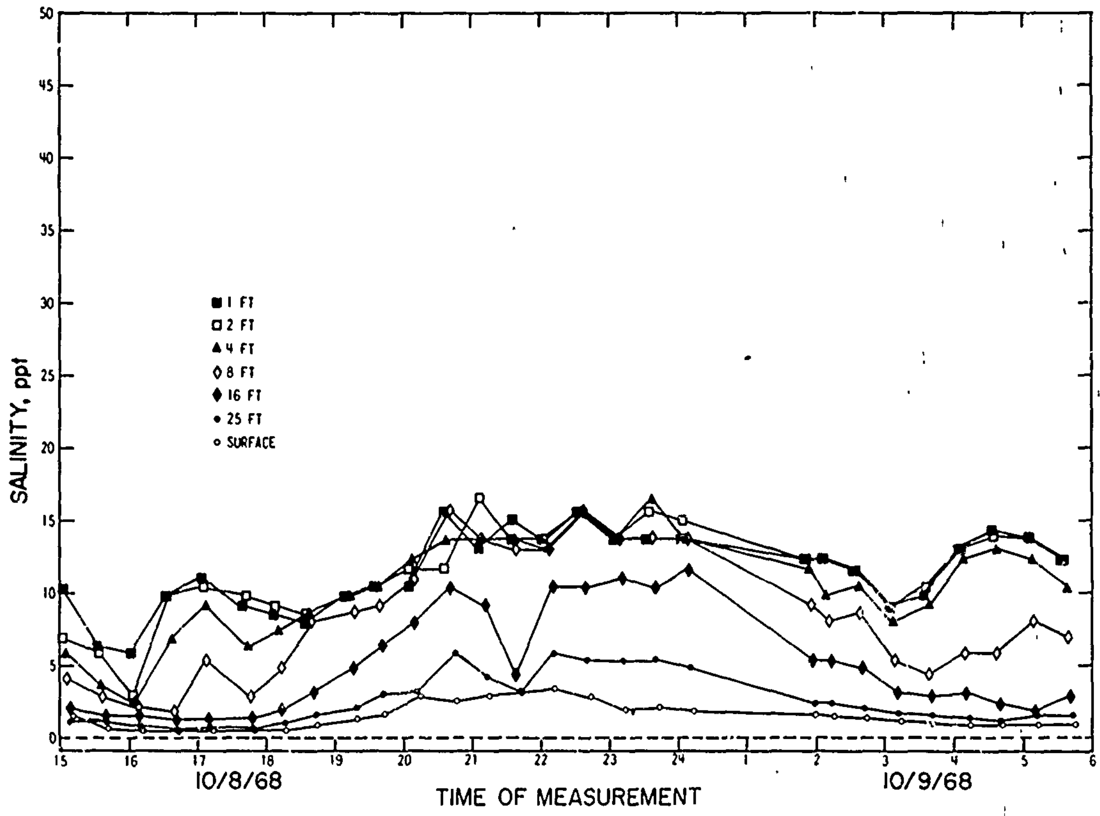


a. Currents



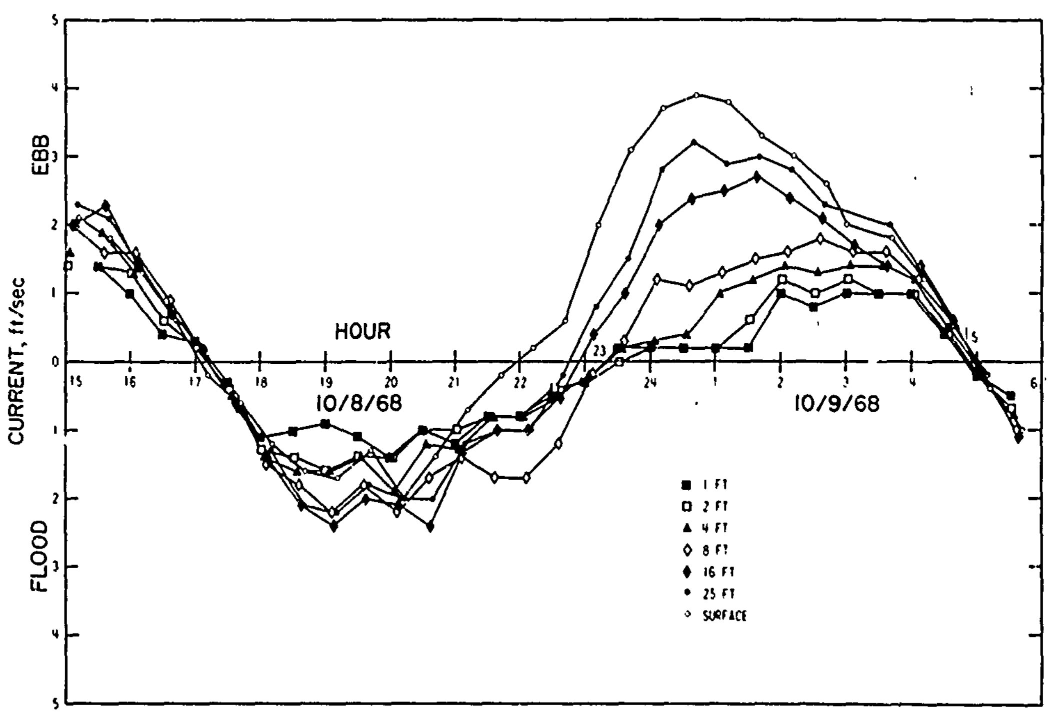
b. Suspended sediments

Fig. 10. Currents, suspended sediments, and salinities at sta 125+500 during a mean tide (Continued)



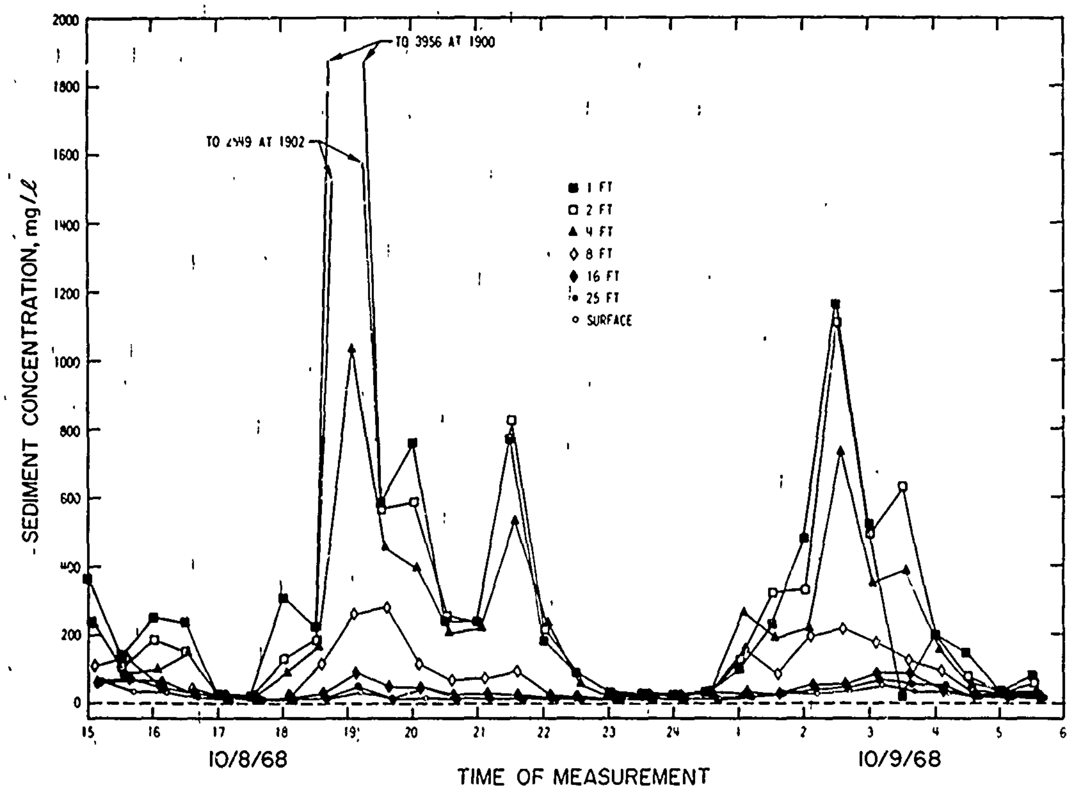
c. Salinities

Fig. 10. (Concluded)

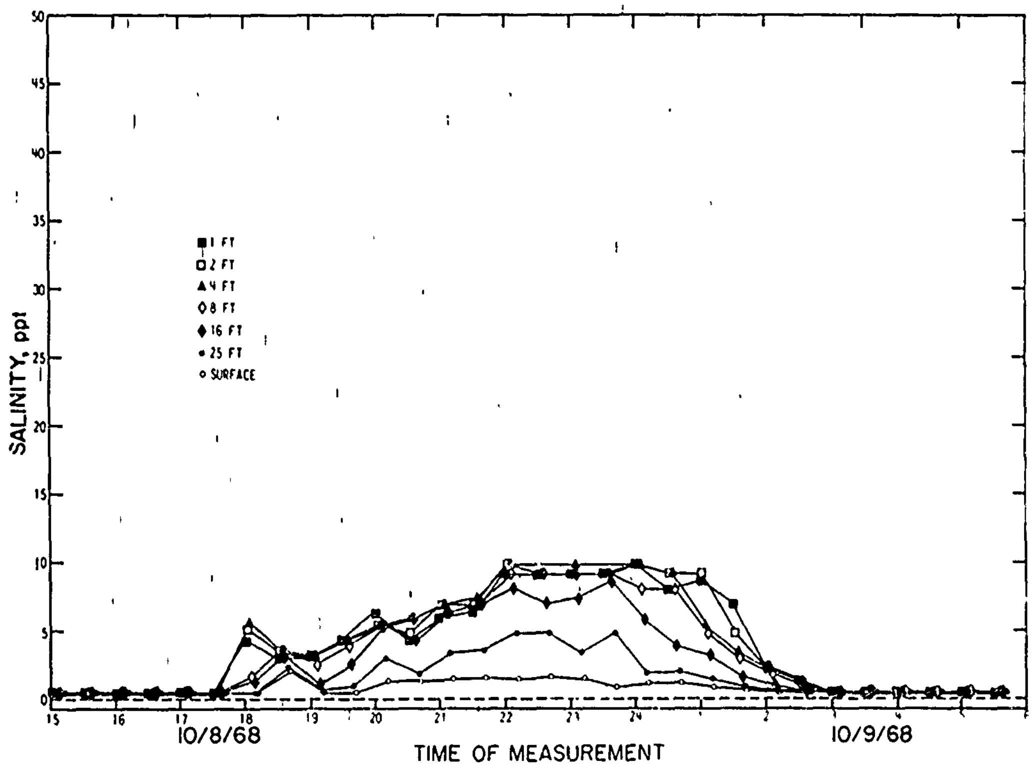


a. Currents

Fig. 11. Currents, suspended sediments, and salinities at sta 109+667 during a mean tide (Continued)



b. Suspended sediments



c. Salinities

Fig. 11. (Concluded)

more marked flood predominance, that is, the durations of flood flows are longer and the currents during flood are much greater than those during ebb, and the ebb currents up to 4 ft above the bed are 1 fps or less.

The suspended sediment concentration curves show that almost no sediment was suspended during ebb flows, whereas significant amounts of sediment were suspended and transported during flood flows near the bed. Almost complete rectification of sediment transportation in the upstream direction was facilitated by the bias in near-bed currents and by the shear strength of the cohesive bed.

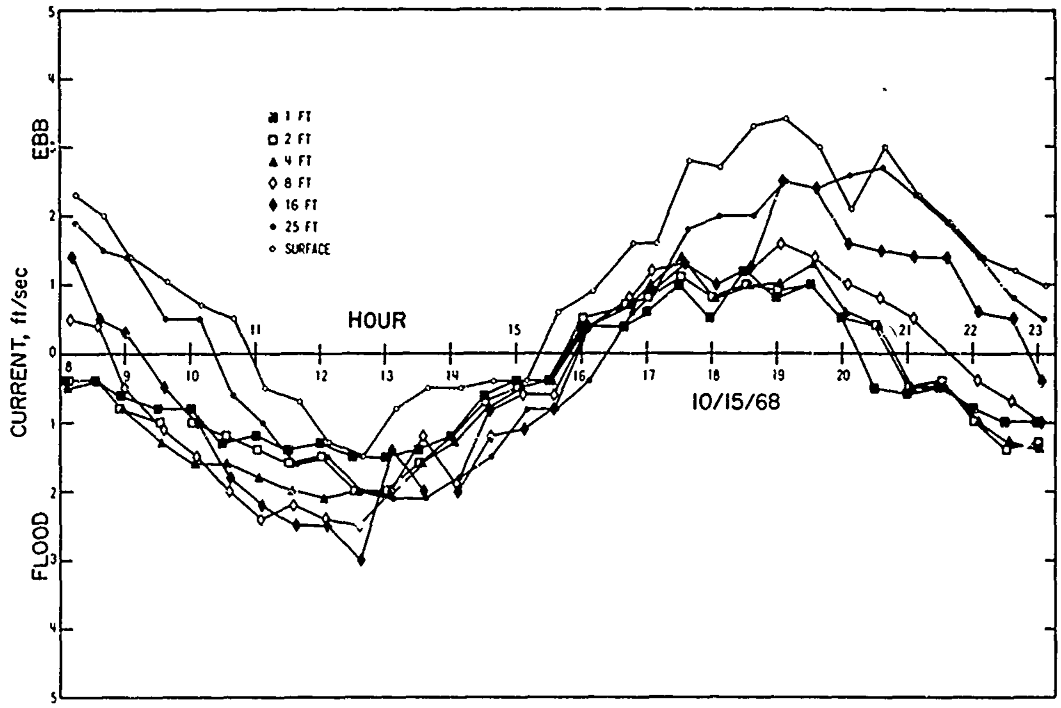
The salinities at sta 130+500, presented in fig. 9c, were slightly greater near the bed and lower near the water surface during mean tide than during spring tide.

The data from sta 125+500 in fig. 10 also show, in comparison with those obtained at this station during spring tide and presented in fig. 7, stronger flood bias in near-bed currents, lower suspended sediment concentrations, greater differences between the suspended sediment concentrations during flood and ebb, and generally higher salinities near the bed.

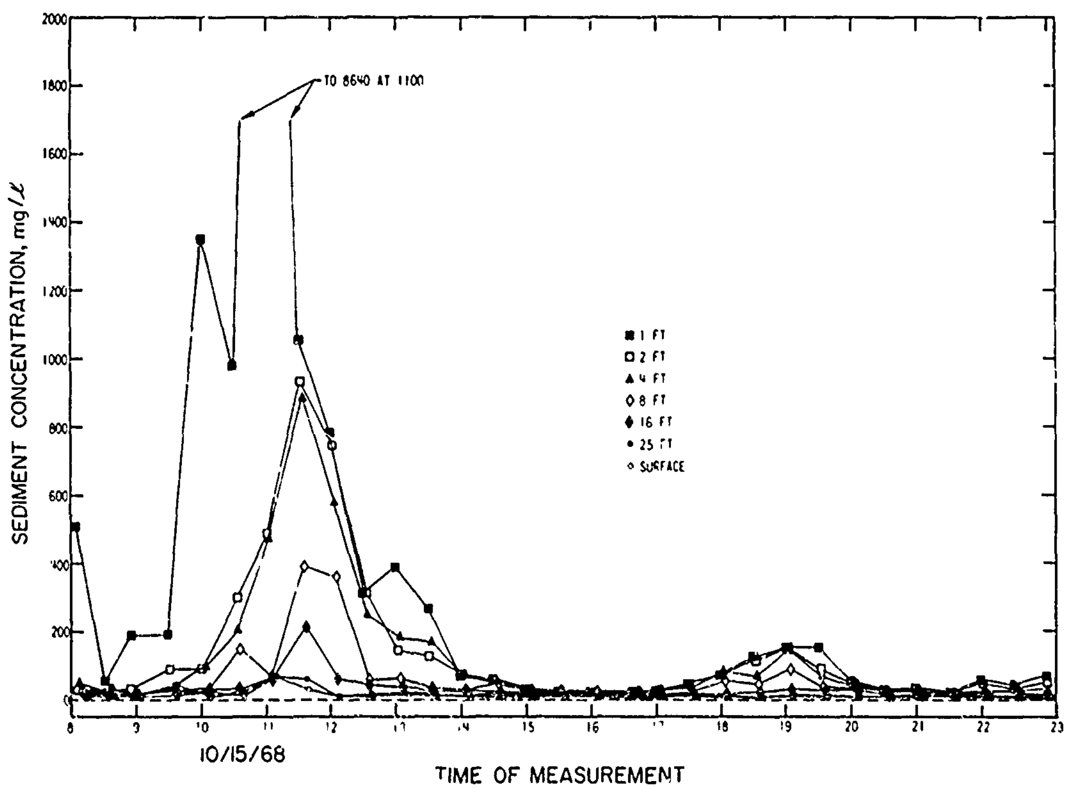
The data from sta 109+667 show, when compared with the data in fig. 8, slower currents, lower suspended sediment concentrations, and higher bottom salinities over a greater portion of the tidal cycle.

The lower suspended sediment concentrations at sta 130+500 and 125+500 observed during mean tide with slightly higher near-bed currents, comp[illegible] with spring tide observations, indicate that the supply of sediment from downstream was limited. Possibly the lower currents associated with the reduced tidal range or the occurrences of an east wind during the spring tide and a northwest wind during mean tide conditions altered the suspension of sediment in the shallow areas.

Measurements at Neap Tide. The data obtained from the field measurements made during a neap tide are presented in figs. 12, 13, and 14. These figures show that flood currents were predominant near the bed under this condition at all three stations. They also show that sediments were suspended during the higher bottom currents and settled to remain deposited for long periods near times of slack water, with marked

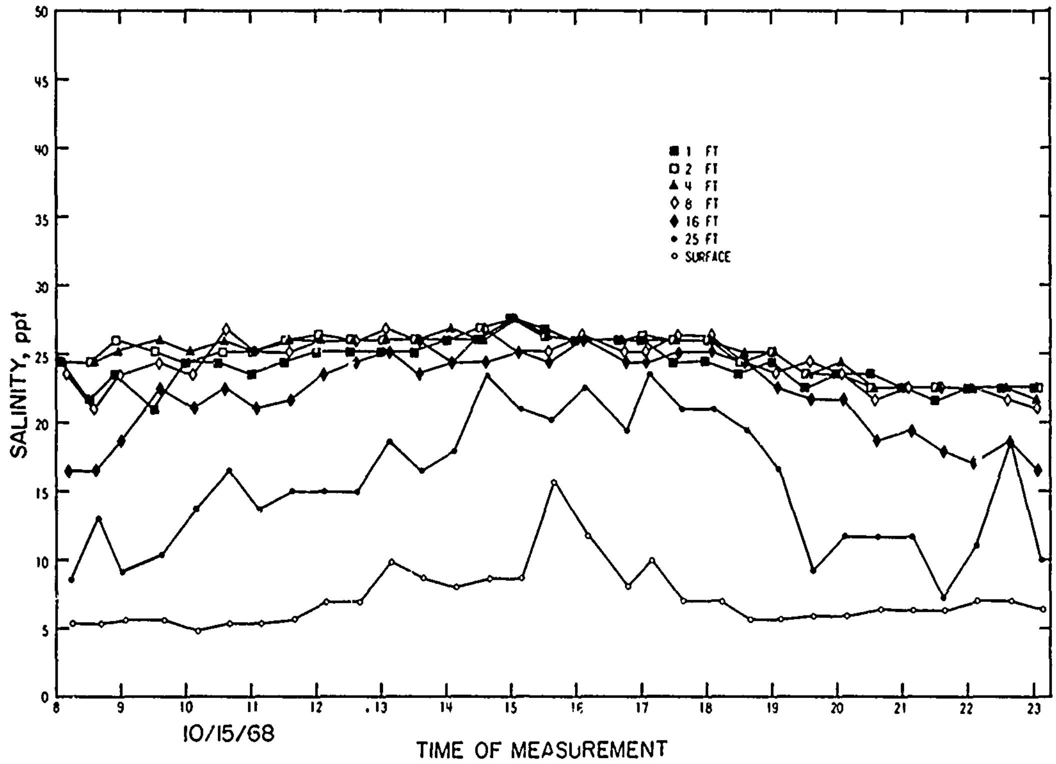


a. Currents



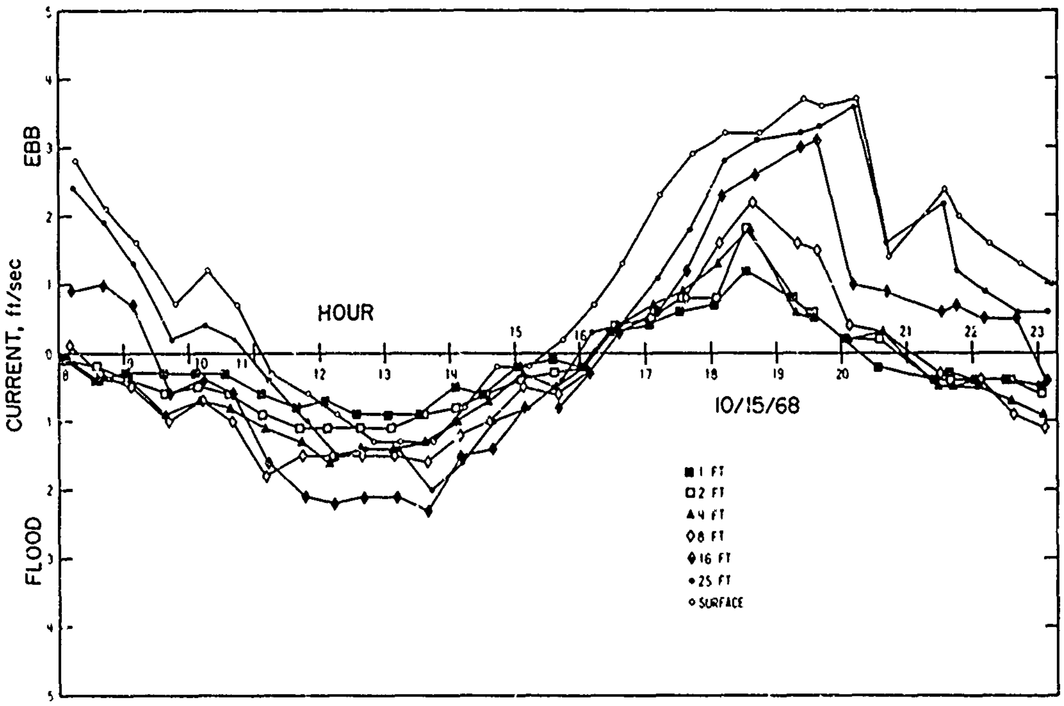
b. Suspended sediments

Fig. 12. Currents, suspended sediments, and salinities at sta 130+500 during a neap tide (Continued)



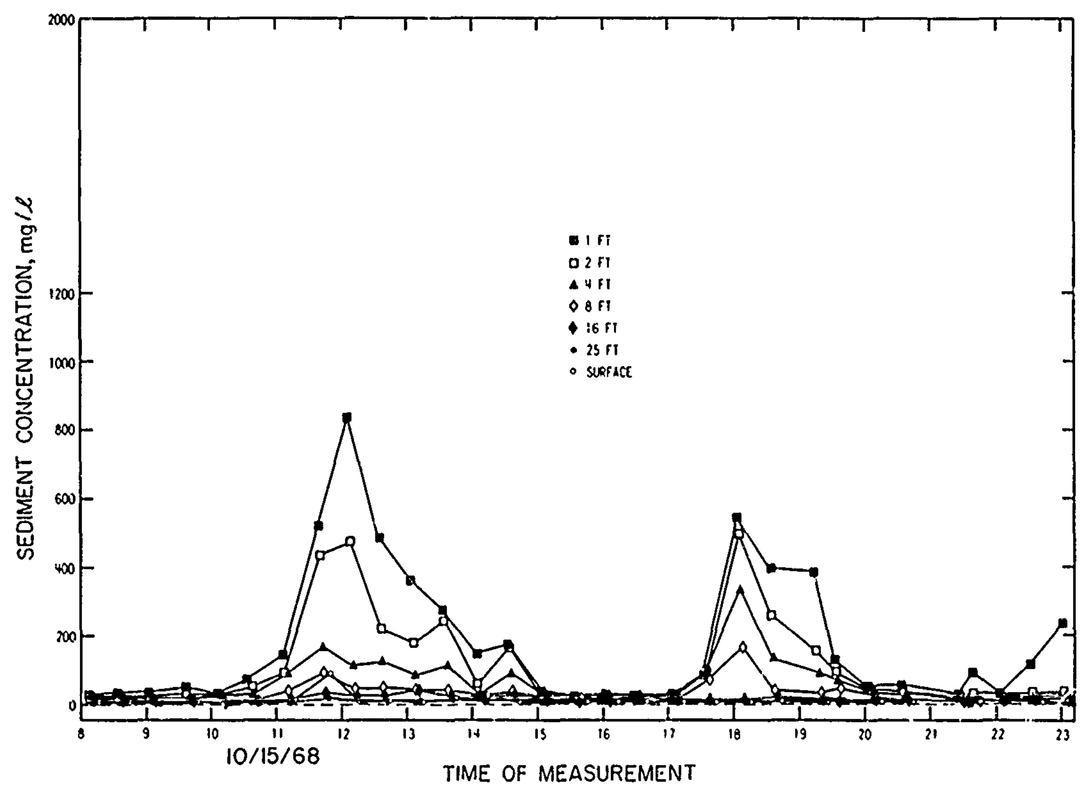
c. Salinities

Fig. 12. (Concluded)

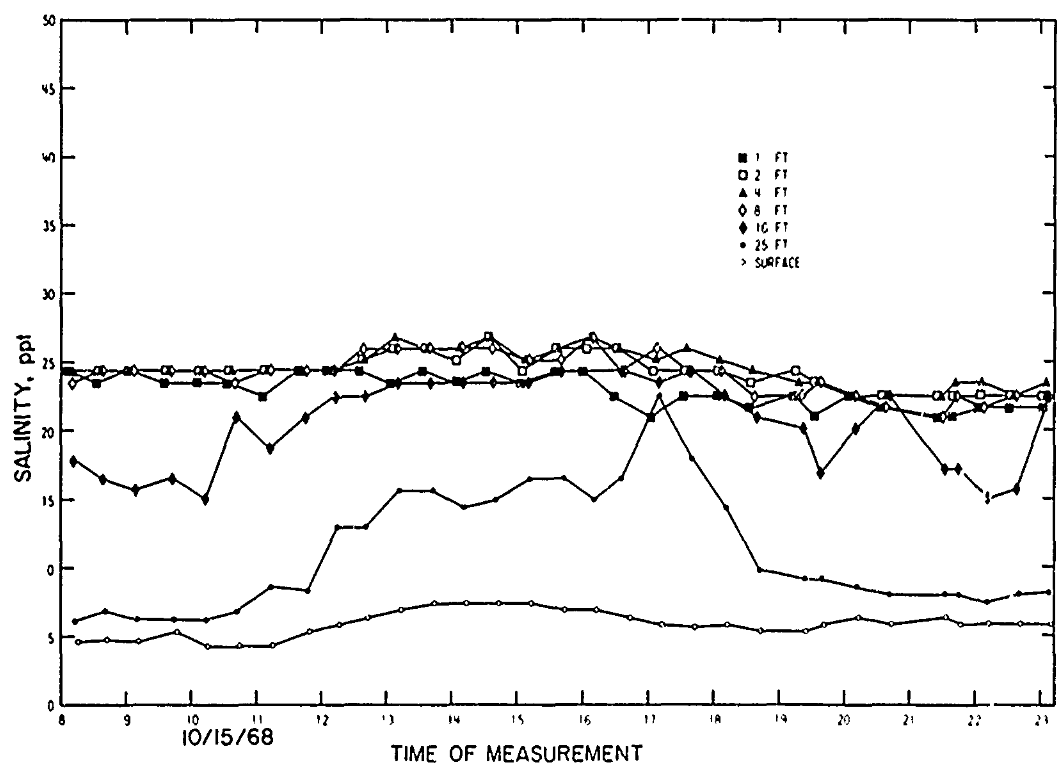


a. Currents

Fig. 13. Currents, suspended sediments, and salinities at sta 125+500 during a neap tide (Continued)

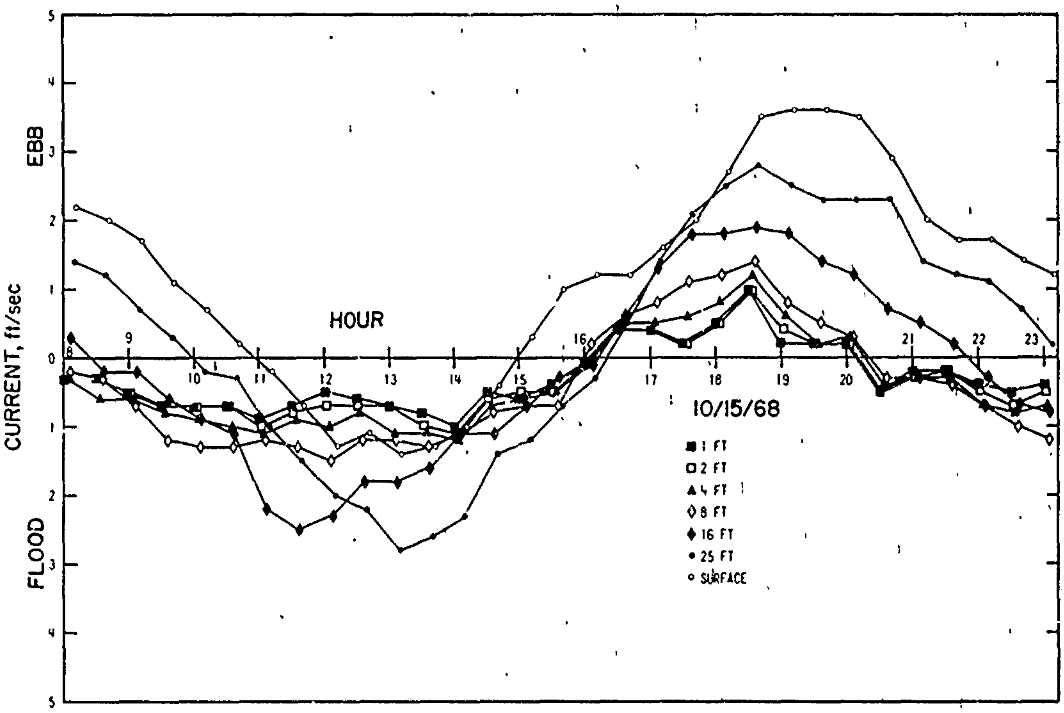


b. Suspended sediments

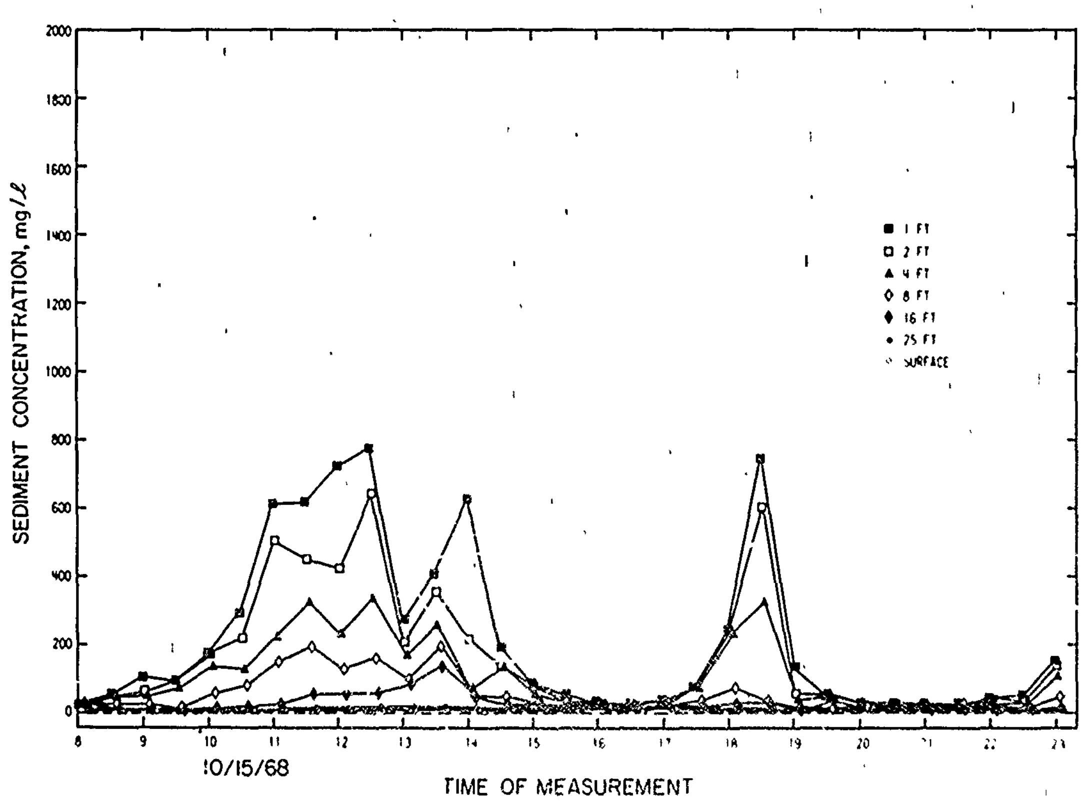


c. Salinities

Fig. 13. (Concluded)

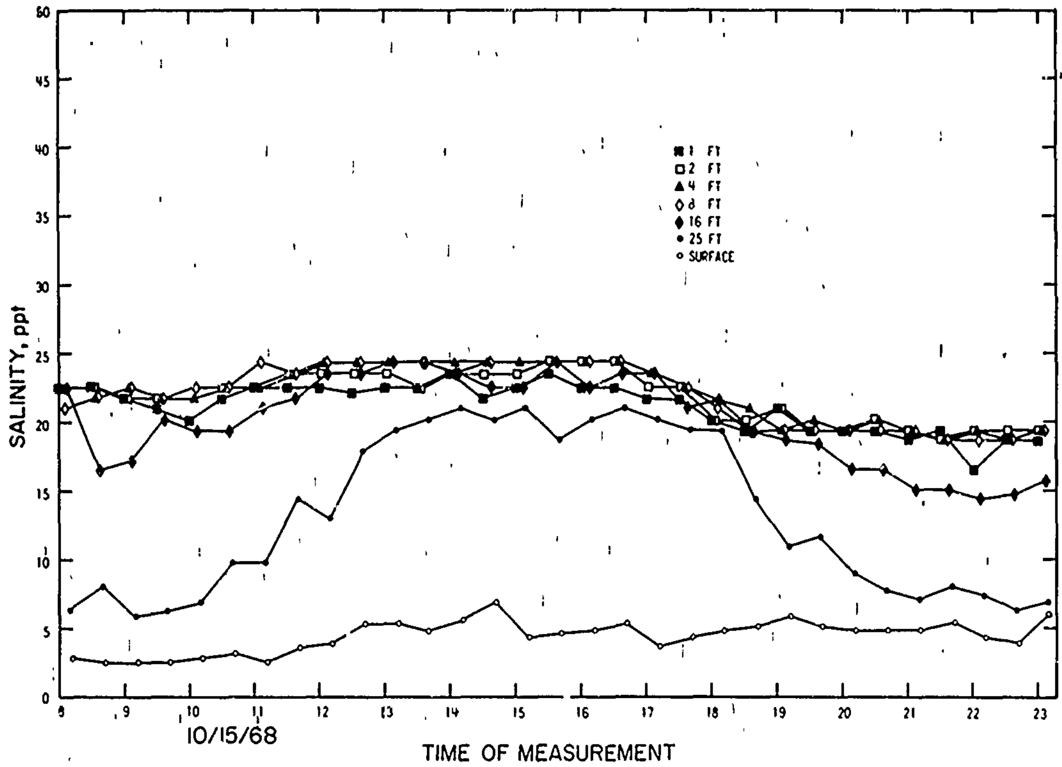


a. Currents



b. Suspended sediments

Fig. 14. Currents, suspended sediments, and salinities at sta 109+667 during a neap tide (Continued)



c. Salinities

Fig. 14. (Concluded)

rectification or net transport upstream at all three stations. The suspended sediment concentrations near the bed were generally lower than those observed during the mean tide observations. Bottom salinities were much higher and showed less variation during the tidal cycle than did the salinities observed during the tides of greater amplitude.

Overview

The data presented in figs. 6 to 14 show that under the hydraulic and salinity conditions prevailing during tidal ranges from 8.6 to 5.4 ft, and with a nearly constant freshwater outflow around 7000 cfs, flocculation processes (aggregation and cohesion) determine the mode of sediment transport in the study area. In every case, the suspended sediment concentration in the 8 ft or so of water immediately above the bed fell rapidly to low values as the tidal currents near the bed approached slack. The fine particles found to comprise the shoal (more than half

less than 2 microns diameter) would not have settled in so short a time if they were not aggregated to form clumps of appreciable size.

As the material at higher elevations above the bed settles, it contributes to the concentration of the suspension measured at lower elevations. When the suspended sediment figures are examined for evidence of settling velocity, decreases of concentration with both time and depth should be considered. For example, the concentration at 4 ft above the bed at 1830 in fig. 14b was sharply reduced at 1900. It is more significant that the concentrations at 2 ft and at 1 ft are lower at 1900 than that at 4 ft at 1830. Most of the material at 4 ft settled through the 2-ft level and much of it settled through the 1-ft level in half an hour; and it settled against the turbulent fluctuations and concentration gradient generated by the slow current shown in fig. 14a. A 2-micron clay particle settles in still water approximately 1 ft in 6 hours.

The suspended sediment concentration at 1 ft above the bed remained close to zero after slack until the near-bed current, therefore the shear on the bed, was sufficient to resuspend the deposit, indicating that the bed was cohesive. The bed surface may be regarded as an aggregation of cohesive aggregates. The shear strength of the bed increases rapidly with depth, however, because of consolidation from the increasing weight of the skeleton of particles with depth.[11] The shear stress on the bed increases approximately with the square of the near-bed current, so that when the currents are sufficient to suspend deposited sediment, even slightly faster currents during flood than during ebb will result in suspension of more sediment during flood and will cause the upstream transportation shown. The suspended material will retain much of the aggregation it had on settling and will settle again at the next opportunity.

The transportation process shown requires for its initiation suspended aggregates of appreciable size. The relevant questions are:

a. How and where did the disperse streamborne particles form aggregates?

b. Can knowledge of the flocculation processes be utilized to control shoaling and enhance water use?

The following three chapters are directed toward these questions.

IV. DISCUSSION

Flocculation Processes

Flocculation of suspended sediment particles requires two processes. The suspended particles must collide with one another repeatedly, and the colliding particles must cohere. Waterborne clay mineral particles are mutually cohesive when either the suspending water is almost devoid of salts or when the cation concentration in the water is sufficient to overcome the mutual repulsion of the clouds of cations attracted by the negative mineral faces.

Typical estuarine sediments are significantly cohesive when the concentration of sea salts exceeds 1 g/ℓ.[11] Much of an estuary has salt concentrations in excess of this value, and once the river waters have mixed with sea water to this extent the particles are cohesive. Aggregates of significant size will not form at salinities above 1 g/ℓ, however, unless conditions exist that cause repeated collisions of suspended particles.

There are three mechanisms of interparticle collision. The most commonly mentioned mechanism is collision due to the jostling of small particles by the thermal motions of the suspending medium. This particle motion, called Brownian motion after its first observer, is easily seen with a microscope. The frequency of collision on one particle by others, I , was described by Whitlaw-Gray and others,[13] as

$$I = \frac{4kTn}{3\mu} \tag{2}$$

where

k = Boltzman's constant

T = absolute temperature

n = number of suspended particles per cubic centimeter

μ = viscosity of the water

All particles are considered to be the same size in equation 2 for simplicity. The number of collisions on a particle per second at the prevailing temperature is

$$I = 6 \times 10^{-12} n \tag{2a}$$

which shows that the number of particles per cubic centimeter must be large for this mechanism to prevail. If the average particle is 0.25 micron diameter, for example, the time between collisions for dispersed particles at a concentration of 200 mg/ℓ is 16 sec.

The second mechanism of interparticle collision is that due to internal shearing, or local velocity gradients in the fluid. Particles slightly displaced in the fluid along a velocity gradient will have relative motion such that the particle in the faster moving fluid will catch up to the slower particle. Collision will occur if the paths of the particle centers are displaced less than the sum of their radii. This sum is called the "collision radius," R_{ij} , between i-size and j-size particles. The frequency of collisions on a j-size particle, J , by this mechanism was derived by Smulschowski[14] and is

$$J_j = \frac{4}{3} n_i R_{ij}^3 G \tag{3}$$

where G is the <u>local</u> velocity gradient. The significant feature of this relation is the strong effect of the collision radius on the frequency of collision. The collision radius for a large aggregate and an individual clay particle is larger than that between two clay particles, with the result that in a shearing suspension containing large numbers of small particles so that n is large, together with relatively few large aggregates, the large aggregates will appear to gather the primary particles and grow even larger.

The third mechanism of interparticle collision is the collision resulting from differential settling velocities of particles. Larger particles settling through a suspension of smaller particles collide with the smaller particles if the size difference is not too great. The collision on a settling particle per second, H , due to this mechanism is

$$H = \pi E R_{ij}^2 V n \tag{4}$$

where

E = capture coefficient

V = relative velocity between particles

Fuchs[13] shows that the capture coefficient probably falls rapidly as the ratio of the particle radii diminishes from one but is enhanced when the Reynolds number, based on the radius of the smaller particle, exceeds one because of the wake produced by the leading particle. The important features of this process are the dependencies on R and n. Here again the large particles gather smaller ones. This mechanism contributes to the observed rapid clarification of water at slack.

All three of these mechanisms operate in an estuary where the water is seldom still. Differential settling is probably important only when the aggregation is already far advanced, and during near slack flows when the local shearing rate is low. The relative effectiveness of internal shearing and Brownian motion can be seen from the ratio

$$\frac{J}{I} = \frac{\mu R_{ij}^3 G}{kT}$$

When $G = 1\ \mathrm{sec}^{-1}$, and the temperature is that at Savannah Harbor, this ratio is one for $R_{ij} = 0.77$ micron. Even at this very low shearing rate and for clay-size particles, internal shearing is as important as Brownian motion. As aggregates become larger, or as the shearing rate increases, internal shearing rapidly becomes the dominant mechanism for collision. Brownian motion can contribute during the initial stages of aggregation of riverborne particles when the number concentration is large, but the formation of large aggregates in an estuary is very predominantly due to internal shearing.

Internal shearing also affects the structure of suspended aggregates and thereby their density and shear strength. It was found during a rheological study[11] that aggregate structures could be described as follows. Primary mineral particles added one at a time to form a uniform aggregation are designated a "primary particle aggregate" or a zero-order aggregate. When sufficient numbers of primary particle aggregates exist to collide with one another, aggregations of primary aggregates form.

These are designated first-order aggregates. The first-order aggregates will include interaggregate pores in addition to the intermineral particle pores of the primary particle aggregates and will therefore be less dense. Shear stresses will be concentrated at the interaggregate contacts so that the apparent shear strength of the first-order aggregates will also be less than that of the zero-order aggregates.

If sufficient numbers of first-order aggregates exist to facilitate their aggregation with each other, second-order aggregates are formed that have lower densities and shear strengths than did the first-order aggregates, and so on. First-, second-, and third-order aggregates were easily observed in a concentric cylinder viscometer containing concentrated suspensions of estuarial sediments. Densities and shear strengths for each order were calculated.

Aggregates suspended in a shearing fluid rotate; and if the forces causing rotation exceed the shear strength of the contact area formed on collision, a bond will not be formed. If the stresses on an aggregate already formed exceed its apparent shear strength, the aggregate will be rendered until a lower order having the necessary strength remains. An aggregate of a given order can exist to some maximum shearing rate beyond which only Tower orders are resistant. Third-order aggregates typically withstood shearing rates up to 3 sec^{-1}, second order up to 11 sec^{-1}, first order up to 40 sec^{-1}, and zero order well over 100 sec^{-1}. Higher shearing rates favor both increased collision frequencies and denser aggregates.

A freshly deposited cohesive bed surface is one order of aggregation greater than that of the depositing aggregates, so that it is weaker. When such a bed is eroded, the weaker bonds (i.e. those formed when aggregates contact the bed) would break first, resuspending aggregates having the same order of aggregation as those deposited, provided they could exist in the flows.

Suspended aggregates are free to rotate, so the stress on their surface is less than that on a fixed bed experiencing the same velocity gradient.[11] Because of their freedom to rotate and because the shearing rate in a channel is greatest near the bed, aggregates can be transported

long distances intact and even grow above beds experiencing shear stresses that cause scour.

Aggregation by Brownian motion or by differential settling in the absence of internal shearing requires only that the particles cohere under the very small surface stresses imposed by settling through the water. Such aggregates would be expected to be weak, to be ragged in shape, and to have very low density compared with aggregates formed in shear flow. The shearing rate and the length of time the aggregates are exposed to a particular shearing rate are major factors in the rate of formation and the character of the resulting aggregates, including the shoal surface.

Internal Shearing at Savannah Harbor

Internal shearing in partially mixed flows is most evident in velocity profiles. While steady flow in a tidal estuary exists fleetingly, if at all, it is useful to examine the current profiles during the strengths of flood and ebb and to seek those whose profiles are determined by bottom friction. Under these conditions the steady-flow descriptions can assist interpretation. The straight, uniform channel locations for the current measurements were sought to obtain such profiles.

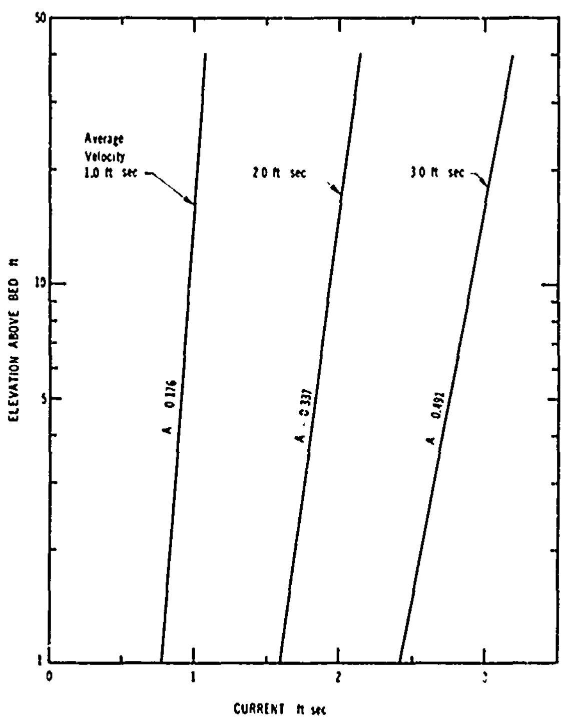


Fig. 15. Current profiles in a 40-ft channel with uniformly dense fluid and hard wall

In order to provide perspective to the data, calculated current profiles that would be expected for uniform steady flow of homogeneous clear water in a 40-ft-deep channel were calculated and plotted as shown in Fig. 15. These curves were calculated for several average velocities from the relation

$$u = \frac{2.30u_*}{k} \log 9.04 \frac{zu_*}{\nu} \qquad (5)$$

where

u = horizontal temporal mean current at z elevation above the bed

u_* = friction velocity

k = Karman's constant, taken to be 0.4 for fig. 15

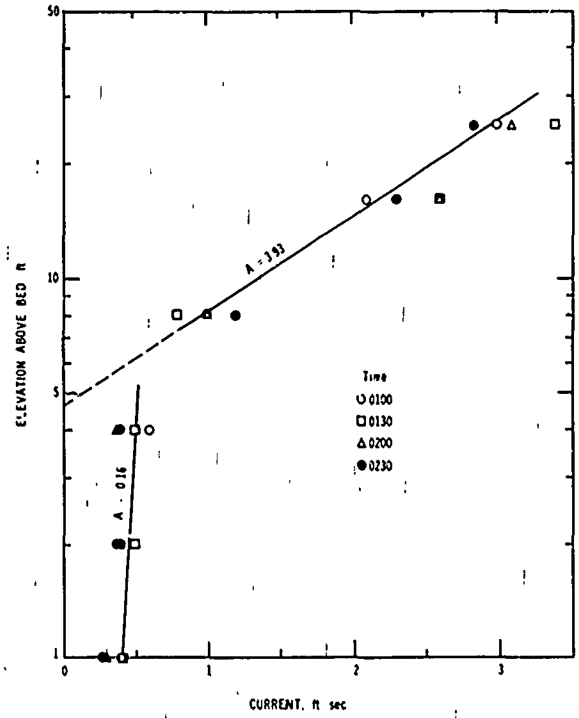
ν = kinematic viscosity, 0.930×10^{-5}

The slopes of the curves, $A = 2.30u_*/k$, are noted on each curve.

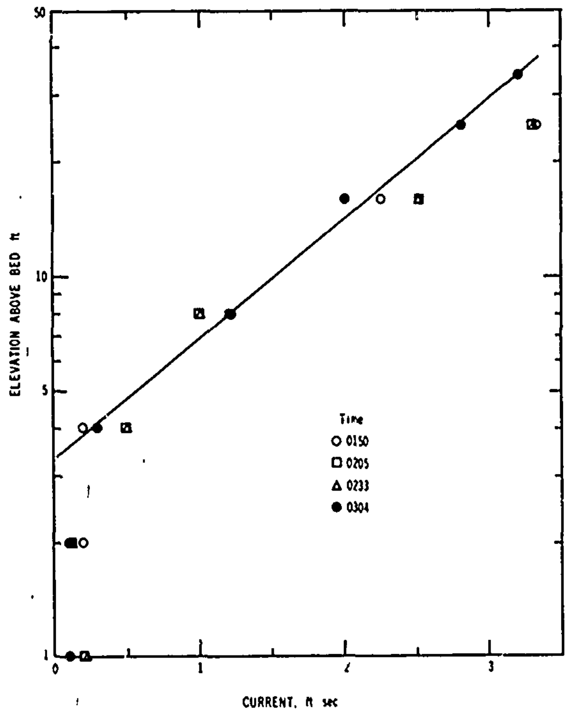
Velocity profiles measured during ebb flows under mean tide conditions are presented in fig. 16. Figs. 16a and 16b show two apparently logarithmic profiles: a nearly normal low-velocity profile from the bed to about 6 ft at sta 130+500 and from the bed to about 4 ft at sta 125+500, and much flatter but approximately logarithmic profiles over the remaining water depth to the surface. Fig. 16c shows a similar profile near the beginning of ebb, with the change in slope at about 2 ft. The slope steadily changed thereafter toward that for uniformly dense fluid. These peculiar profiles result from variations in water densities and the combined influences of tidal and freshwater flows.

The salinities observed during these measurements are plotted in fig. 17. Figs. 17a and 17b show that the lower portions of the salinity profile, corresponding to the low velocity, normal profile portions of figs. 16a and 16b, have almost uniform salinity. The salinity decreases to low values with increasing elevation throughout the remainder of the water above this portion. The continuing decrease in salinity with increase in elevation, and therefore continuing decrease in water density, inhibits vertical velocity fluctuations and thereby reduces vertical momentum transfer. The result is that instead of a concentration of most of the internal shearing near the bed, as it is in typical flows, it is distributed throughout the upper 30 ft or so of the channel.

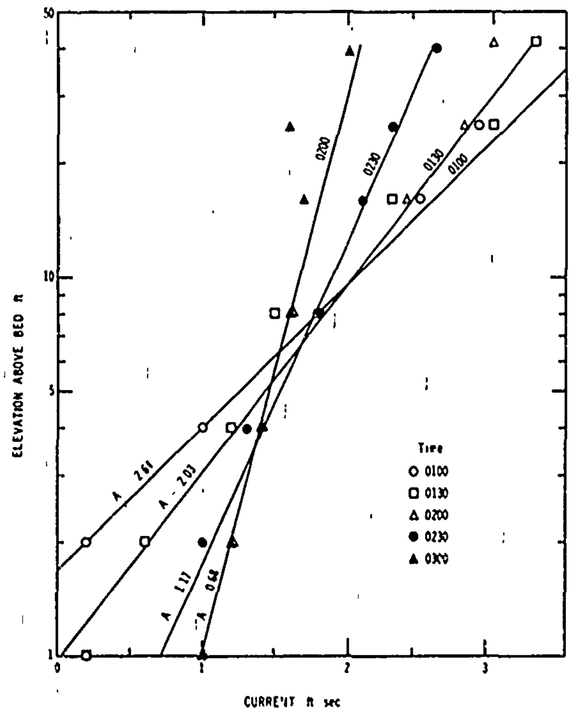
The salinity profiles for sta 109+667, presented in fig. 17c, show a similar profile at 0100, and diminishing salinity at later times until 0300, when the salinity was uniformly that of the freshwater inflow. The change in current profiles shown in fig. 16c is consistent with the increasing uniformity of the density throughout the depth.



a. Sta 130+500

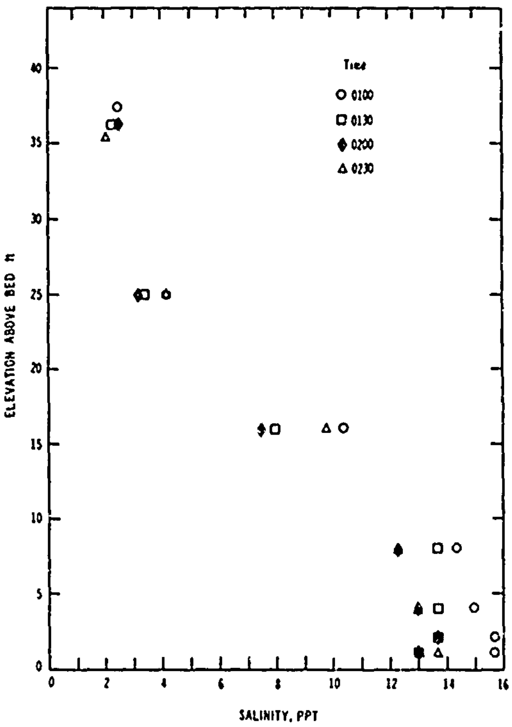


b. Sta 125+500

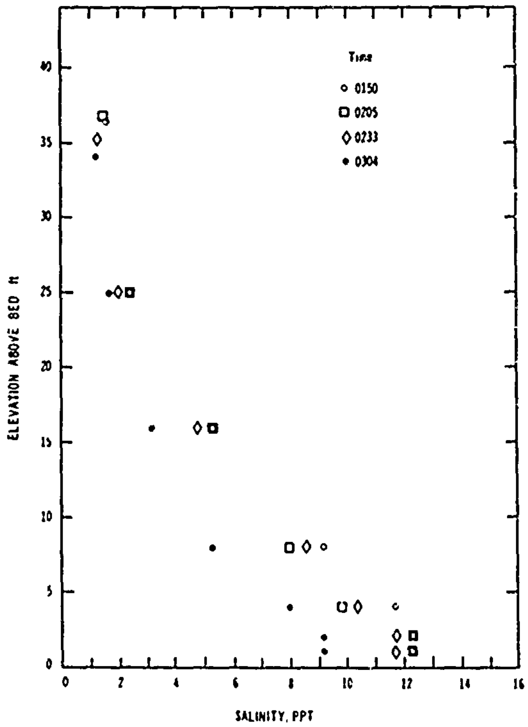


c. Sta 109+667

Fig. 16. Ebb current profiles at sta 130+500, 125+500, and 109+667 during a mean tide

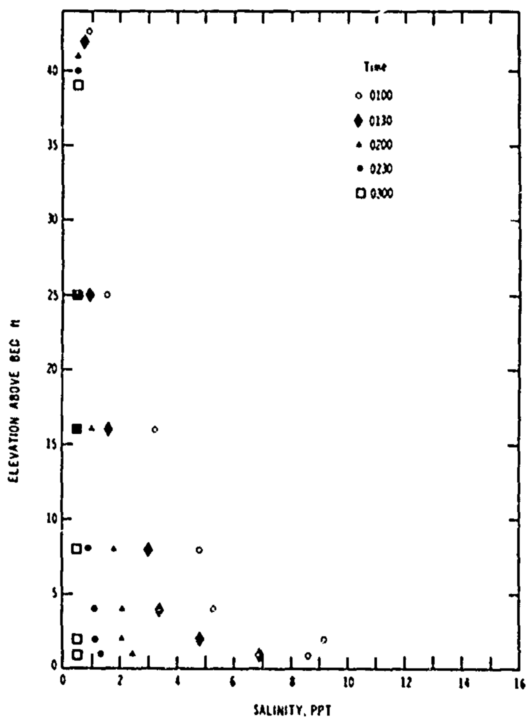


a. Sta 130+500



b. Sta 125+500

Fig. 17. Salinity profiles at sta 130+500, 125+500, and 109+667 during a mean tide ebb



c. Sta 109+667

The salinities near the bed are shown in fig. 17 to diminish with distance upstream, indicating that the intruding salt water is steadily diluted by the overriding fresh water. At the same time, the salinities in the upper region increase with distance downstream, which indicates vertical mixing of the two layers. The nearly uniform densities near the bed indicate that flow in that region is well mixed, whereas the decreasing salinities above that region indicate slow vertical propagation of saline water and dilution by the greater flows near the surface.

The stabilization of flow by the density gradient is characterized by the ratio of inertial forces to gravity stabilizing forces resulting from the salinity gradient. This ratio is the Richardson number

$$R_i = \frac{\left(\frac{du}{dz}\right)^2}{\frac{g}{\rho}\frac{d\rho}{dz}} \tag{6}$$

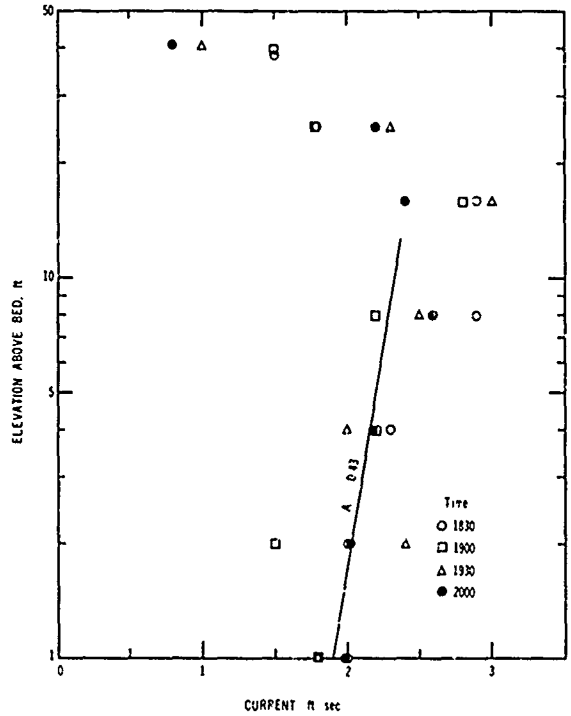
When R_i is less than 1, the flow is laminar. R_i was calculated from the data in figs. 16a and 17a for the flow 10 ft above the bed to be 2, indicating that momentum transfer upward is small.

Current profiles measured during the strength of flood flows are presented in fig. 18. This figure also shows the effects of freshwater outflow near the surface, which opposes flood tidal flow. The slopes of the curves are more than twice those for comparable flows of uniformly dense water, as shown by comparison with the curves in fig. 15.

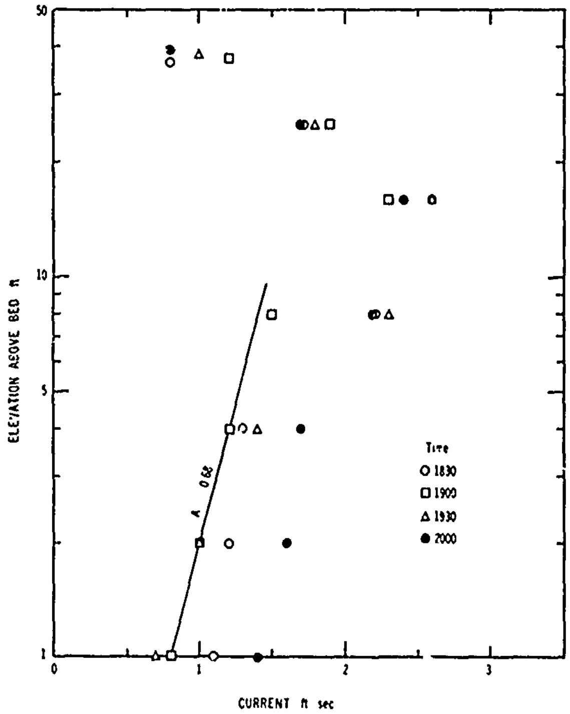
The salinity profiles during the strength of flood are presented in fig. 19, and show that the salinity gradients persist through the water above 4 ft and that the salinities increase almost uniformly as more saline waters move back upstream. Figs. 19a and 19b show that saline water intrusion is most rapid 2 to 4 ft above the bed during flood.

An estimate of the internal shearing in the flows where bed friction determines the profile can be obtained from the observation that the average internal shearing in a fluid, G , is

$$G = \sqrt{\frac{P}{\mu}} = \sqrt{\frac{\tau\frac{d\bar{u}}{dz}}{\mu}} \tag{7}$$

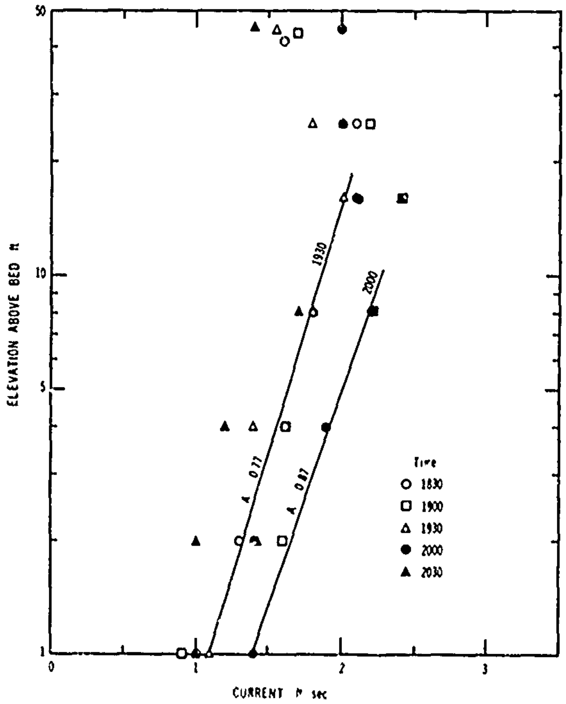


a. Sta 130+500

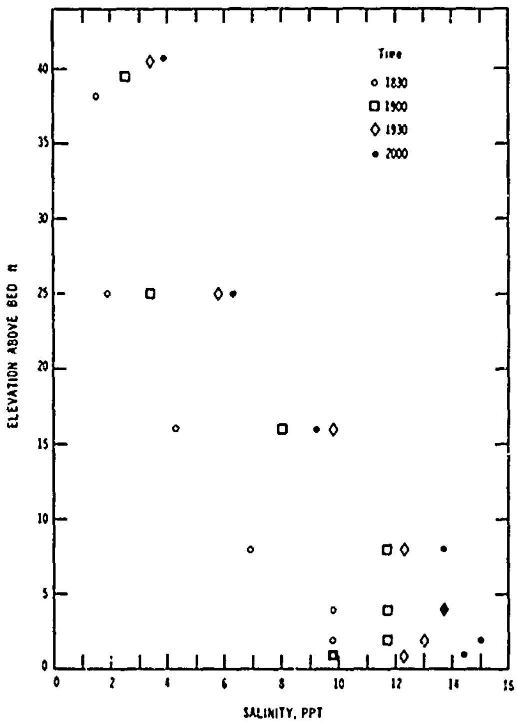


b. Sta 125+500

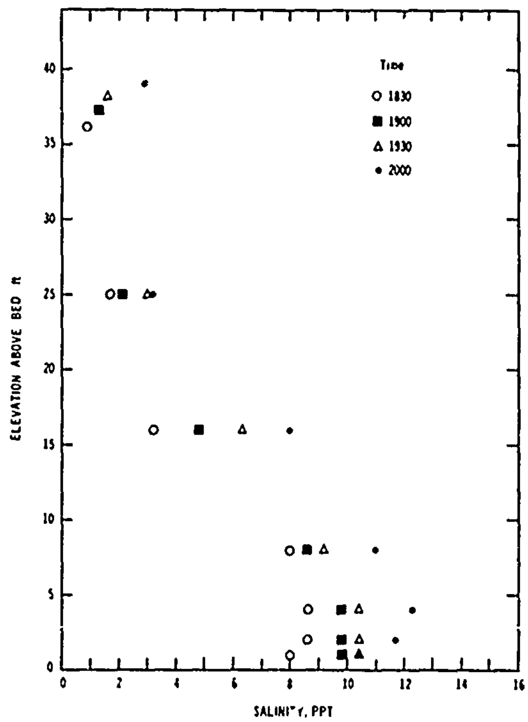
Fig. 18. Flood current profiles at sta 130+500, 125+500, and 109+667 during a mean tide



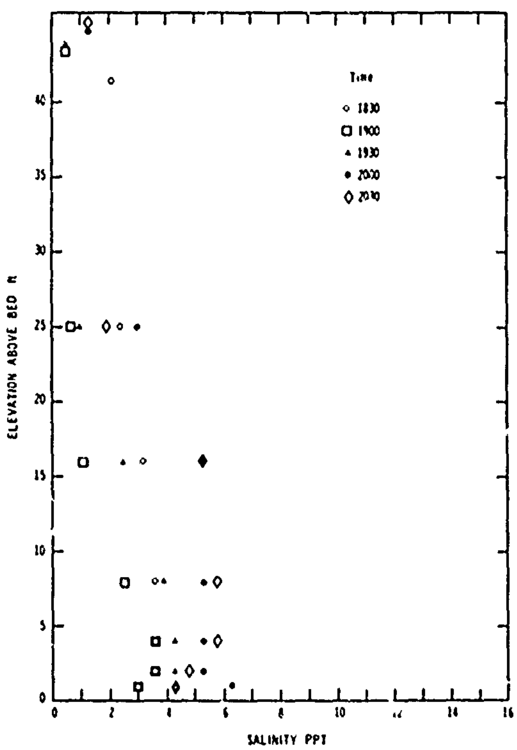
c. Sta 109+667



a. Sta 130+500



b. Sta 125+500



c. Sta 109+667

Fig. 19. Salinity profiles at sta 130+500, 125+500, and 109+667 during a mean tide flood

where

P = energy dissipated per unit volume of fluid

μ = viscosity

τ = shear at any elevation z

τ may be estimated as

$$\tau = \rho u_*^2 \left(1 - \frac{z}{d}\right) \tag{8}$$

where ρu_*^2 is the shear on the bed, and d is the water depth.

$$\frac{d\bar{u}}{dz} = \frac{u_*}{kz} \tag{9}$$

as conventionally described. Combining equations 7, 8, and 9 leads to

$$G = u_* \left(\frac{u_*}{\nu k}\right)^{1/2} \left(\frac{1}{z} - \frac{1}{d}\right)^{1/2} \tag{10}$$

The slopes of the logarithmic curves are $A = 2.30u_*/k$. Substitution in equation 10 leads to

$$G = \frac{kA}{2.30} \left(\frac{A}{2.30\nu}\right)^{1/2} \times \left(\frac{1}{z} - \frac{1}{d}\right)^{1/2} \tag{11}$$

which is more useful for evaluating the velocity profiles.

A plot of the internal shearing in flows with logarithmic profiles calculated from equation 11, using $k = 0.2$, is presented in fig. 20. The shearing rates in uniformly dense clear water flowing at 3 fps with $k = 0.4$ would be close to those shown for $A = 1$ in fig. 20. It is evident from the

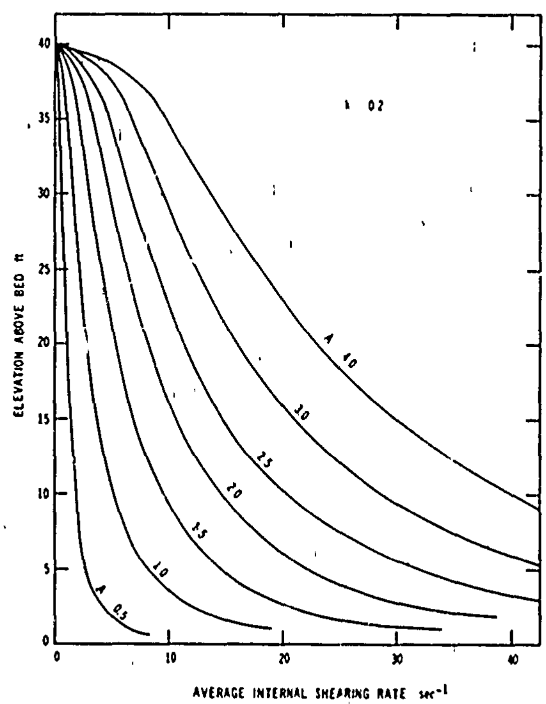


Fig. 20. Average local shearing rates in a 40-ft channel

values of A shown on the current profiles that unusual internal shearing prevails in the study area and that it is most pronounced during ebb flows in the large upper portion of the profile with a salinity gradient.

The calculation above is only an estimate even when the profile is logarithmic because there is no way to determine Karman's constant, k. Measurements of velocity profiles in a flume by Einstein and Ning Chien,[15] using various sizes of sand, showed that at high concentrations of sand conditions near the bed were altered so that k ranged downward to below 0.2. Ippen[16] indicated that increases in the effective viscosity near the bed resulting from suspended particles would reduce k. In addition to the effects of aggregate volumes in the viscous layer and the density gradient due to both salinity and suspended sediment concentration gradients, the cohesive bed undoubtedly deforms in response to pressure fluctuations, giving rise to the probability that the bed itself damps the formation of eddies. The lower value of k appears more appropriate than the 0.4 for the conditions that prevail in the study region.

Bed Shear Stress

Comparison of the lower portions of the current profiles at sta 130+500 and 125+500 during ebb (figs. 16a and 16b) with those during flood (figs. 18a and 18b) clearly shows the difference in near-bed currents responsible for the increased scour of the bed during flood. Lines drawn on figs. 16a and 18a, taken as representative near-bed profiles, have slopes of $A = 0.16$ for ebb and $A = 0.43$ for flood, which compare with the uniform density profiles in fig. 15. k can be taken as 0.4, $A = 2.30u_*/k$, and $\tau_o = \rho u_*^2$, where τ_o is the shear on the bed, and ρ is the water density. These slopes yield bed shear stresses of 0.7 dynes/cm^2 on ebb and 5 dynes/cm^2 on flood. The aggregate shear strengths of Brunswick Harbor sediment, which has cation exchange capacity of 30 milliequivalents/100 g compared with 36 milliequivalents/100 g for Savannah Harbor shoal material† and is probably slightly weaker,[11] are as follows:

---

† Appendix C.

Brunswick Harbor Aggregate Properties

Order of Aggregation	Shear Strength dynes/cm^2	Density† g/cc
0	34	1.164
1	4.1	1.090
2	1.2	1.067
3	0.62	1.056

† Density of interstitial water, 1.025 g/cc.

Beds composed of first-, second-, and third-order aggregates would be scoured by the flood currents, whereas only beds composed of third-order aggregates would be resuspended by the ebb near-bed currents. The magnitude of bed shear stress and its time of occurrence, as well as relative distance of water travel shown by predominance calculations, are important factors determining net transportation of estuarial sediments.

Predominance Curves

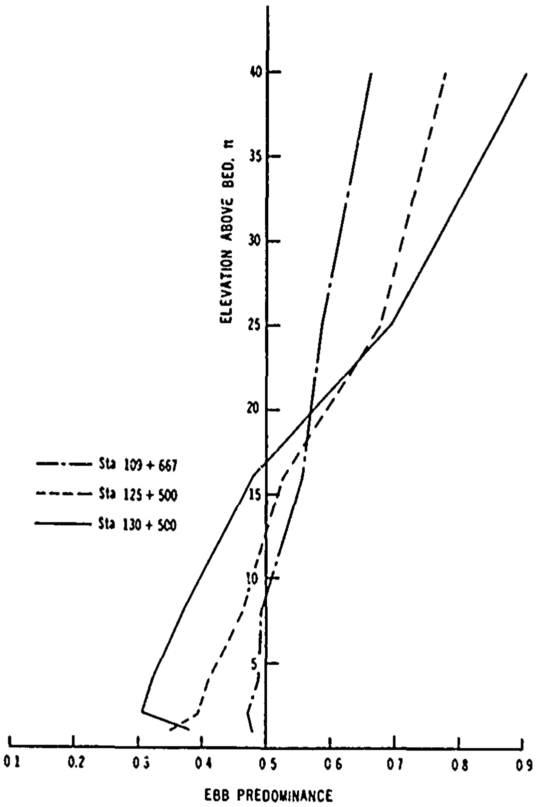
Ebb current predominances were determined by planimeter from the plots in figs. 6-14 as

$$\frac{\int_{\text{Ebb}} u\,dt}{\left(\int_{\text{Ebb}} u\,dt + \int_{\text{Flood}} u\,dt\right)}$$

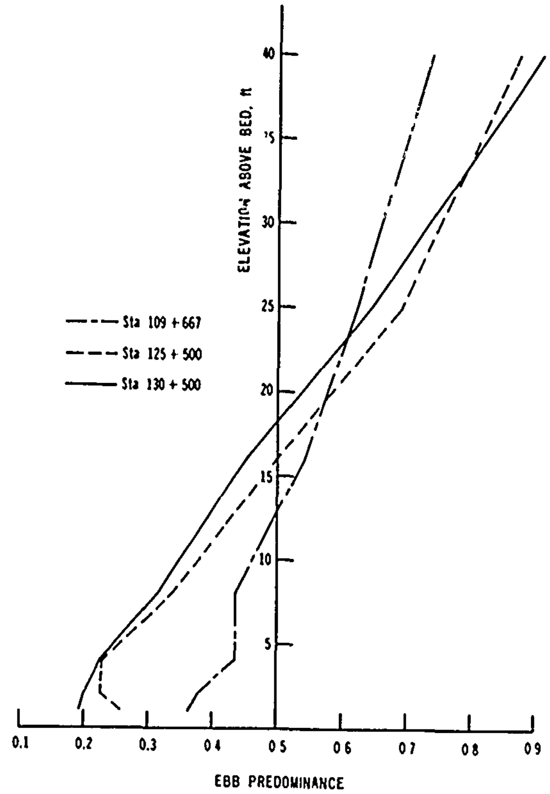
where t is time. These ebb predominances are plotted for each tide condition in fig. 21. The curves from measurements made during spring tide, presented in fig. 21a, show that sta 109+667 was close to the average position of the upstream limit of saline water intrusion, and that bottom currents at the two downstream stations were predominantly in the direction of flood.

The plot of the mean tide data presented in fig. 21b is similar to that in fig. 21a, except that sta 109+667 is farther downstream from the null point and the intercepts on the 0.5 predominance line are closer together, suggesting that with a reduced tidal amplitude the mixing zone is more nearly horizontal.

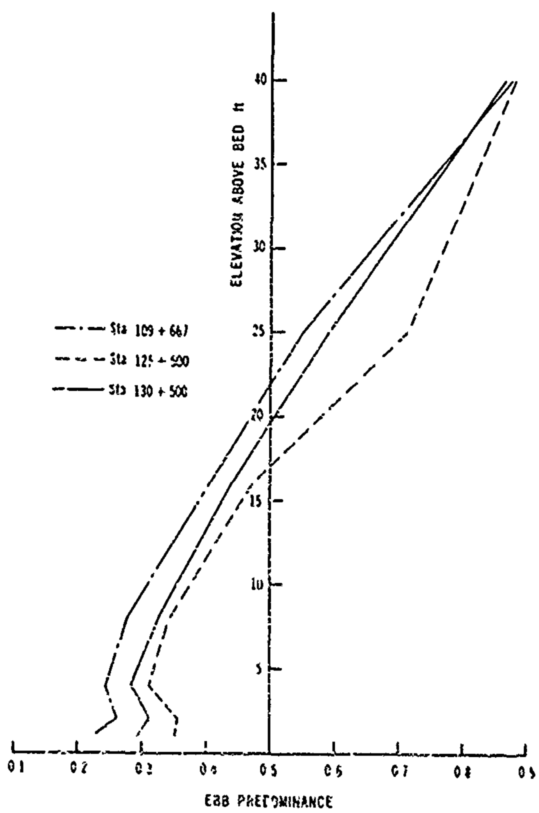
Fig. 21c presents the predominance curves from the measurements



a. Spring tide



b. Mean tide



c. Neap tide

Fig. 21. Ebb predominance in the study area during a spring tide, mean tide, and neap tide

made during the least tidal range. The curves from sta 130+500 and 125+500 are similar to the curves for those stations during mean tide conditions. The curve for sta 109+667, however, shows greater bottom predominance than either downstream station. Fig. 14 shows that there was a very prolonged period of flood near the bed at sta 109+667. No explanation for this peculiar bottom current predominance during neap tide is evident from the data.

The predominance curves show that there is a net upstream movement of water near the bed in the study area which, when combined with the greater scour of deposited material during flood than during ebb, provides net upstream movement of sediment in the lower portions of the flow. The spring tide curves showed also that sta 109+667 was close to the predominance null point under that tide condition.

Floc Settling Velocities

It is already evident from the suspended sediment concentration curves presented in figs. 6-14 that the suspended particles have much greater settling velocities than the individual clay particles which comprise the shoal. An application of steady-state suspended sediment distribution relations to flows showing logarithmic velocity profiles yields further information on floc settling velocities.

The concentration, C_z, of uniform suspended particles in an open channel at elevation z above the bed, relative to the concentration at, say, 1 ft, C_a, can be found from diffusion theory to be

$$\frac{C_z}{C_a} = \left(\frac{a}{d - a}\right)^{\zeta} \left(\frac{d - z}{z}\right)^{\zeta} \tag{12}$$

where

a = reference elevation

d = water depth

$\zeta = w/ku_*$

w = settling velocity of the suspended particles

Flocs suspended in open channel flow under steady conditions would settle to the zone of highest shearing close to the bed where they would be rendered if their structure were too high an order, and diffused upward,

would grow and settle again. Repeated experience would tend to make the aggregates similar, and equation 12 would apply.

Suspended sediment concentrations measured during periods when the velocity profiles were logarithmic were plotted so that distributions described by equation 12 would fit a straight line, as shown in fig. 22.

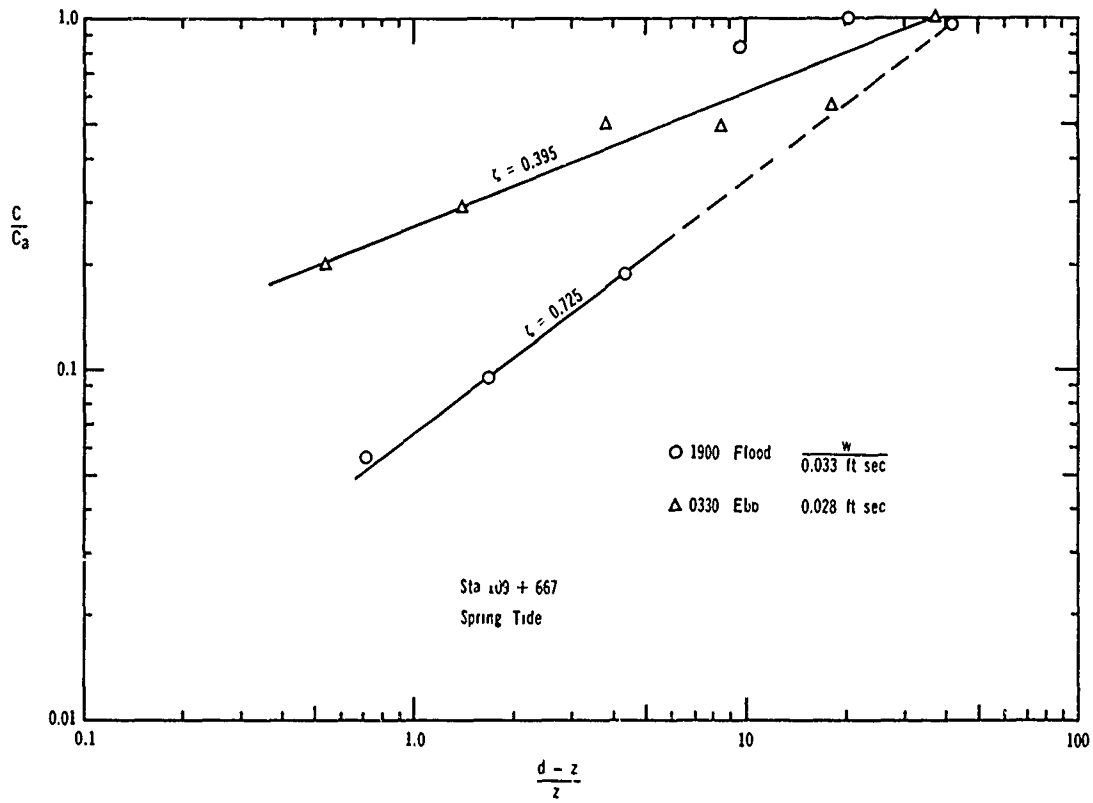


Fig. 22. Plot to find settling velocities of flocs

The slopes of the best straight-line fit were then used to find the settling from the slope of the velocity profile, A, and values of k of 0.4 by means of the relations $u_* = kA/2.30$, and $w = ku_*\zeta$, so that $w = \zeta Ak^2/2.30$. Some of the plots had better fits to straight lines than that in fig. 22, but there were fewer profiles than anticipated that would meet both the criteria of logarithmic velocity profiles and log-log plots that fit equation 12.

The settling velocities calculated from the best fits under each tide condition are summarized below. These few settling velocities appear to fall in groups. Five fall between 0.012 and 0.017, averaging

0.015 fps; seven fall between 0.028 and 0.047, averaging 0.036 fps; and four fall between 0.084 and 0.151, averaging 0.11 fps. Brunswick Harbor first-order aggregates have a density of 1.090 g/cc when suspended in water having a density of 1.025 g/cc. The Stokes settling diameters calculated from these densities are 1.0, 0.6, and 0.4 mm for settling velocities of 0.11, 0.037, and 0.015 fps, respectively. These aggregates should be visible to the naked eye. The diameters would have been half those calculated above if $k = 0.2$ had been used to calculate the settling velocities.

Station	Aggregate Settling Velocities, fps Spring Tide	Mean Tide	Neap Tide
109+667			
Ebb	0.028	0.038	0.030
Flood	0.033	--	0.012
125+500			
Ebb	0.014, 0.013	0.091	0.084
Flood	0.033	0.017	0.047
130+500			
Ebb	0.151	--	0.016
Flood	0.098	--	0.040

Note: Aggregate settling velocities were calculated from equation 12 using $k = 0.4$.

An 0.6-mm first-order aggregate contains about half a million clay particles. Even though there is a large amount of scatter in these data, it can be concluded that large aggregates have formed.

Suspended Sediment Concentration

All three processes that cause collision of suspended mineral particles have rates of collision directly proportional to the suspended sediment concentration by number. The concentration of suspended particles by weight in the study area ranged from tens of milligrams per liter to grams per liter levels. A clay mineral particle weighs about 10^{-11} to 10^{-12} g, and particles dispersed in river water at a concentration of 100 mg/ℓ, for example, would have a number concentration from 10^7 to 10^8 particles per cubic centimeter. Collisions by Brownian motion would occur initially at $I = 6 \times 10^{-5}$ to 6×10^{-4}

per second, or one collision every 4.5 to 0.45 hr for this range in numbers. An aggregate containing half a million clay particles would not form very rapidly.

If the shearing rate averaged 10 per second, then for R_{ij} = 2 microns, $J = 10^{-3}$ to 10^{-2} per second, or say at most, one every 100 sec. Such aggregation would still not account for the formation of large aggregates directly from material suspended in river water unless the aggregation took place over a long period of time. Higher concentrations by number, and at least a few large "seed" flocs that would provide large values of R_{ij}, are required to form aggregates at rates that would account for shoaling where river and ocean waters mix. The feedback mechanism demonstrated by the data presented in figs. 6-14 provides both high concentrations and large collision radii, and the high shearing rates distributed over a large volume in the channel provide extended periods during which the disperse riverborne particles can be gathered by the aggregates returning from downstream. If the returning aggregates were 20 microns in diameter, for example, the collision radius with a dispersed clay particle would be approximately 11 microns, and two collisions per second would occur on each aggregate. Larger aggregates, greater numbers of aggregates, or increased shearing rates would increase the collision frequency.

This chapter presented the factors that determine the rate of aggregation of suspended particles and showed that conditions in the waters of the study region are such that cohesion, frequency of collision, and times for collisions to occur are sufficient for the formation of large aggregates. The settling velocities calculated from the suspended sediment concentration profiles are much greater than those of individual particles that comprise the shoals and show that aggregates are formed from a large number of collisions. These calculated settling velocities are consistent with the rapid clarification of the waters during times near slack that were shown in Chapter III.

The aggregates settle to form the bed surface. The shear strength of the bed surface depends on the shear strength of the cohesive aggregates and their susceptibility to crushing or particle rearrangement

with depth of overburden. The properties of the suspended aggregates, therefore, determine the shears necessary to resuspend thin deposits formed when they settle to the bed.

It can be concluded that at Savannah the settling velocities of the suspended material and the ease of resuspending deposited material, and therefore particulate material transport and accumulation, are determined by flocculation processes.

V. TRANSPORTATION AND SHOALING PROCESSES IN THE STUDY AREA

The field data are combined in this chapter with the concepts provided in the discussion to form a qualitative description of the sediment transportation processes in Savannah Harbor. A schematic diagram summarizing these processes is presented in fig. 23, which represents the freshwater-saltwater mixing zone with dispersed suspended sediment entering in fresh water from the left and loss of suspended sediment to the ocean on the right. Neither the sediment input nor sediment loss is implied to occur at steady rates.

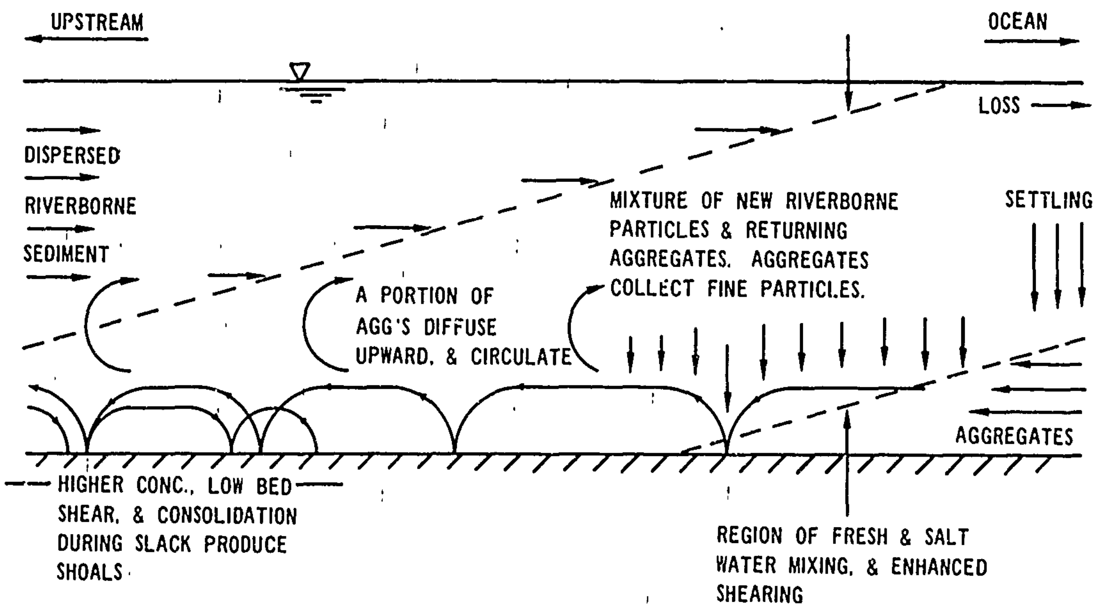


Fig. 23. Transport and shoaling processes in the study area

It is convenient to consider first the aggregated suspended sediment returning upstream with tidal currents shown at the lower right in fig. 23. These sediments originate from shallow areas disturbed by wind-generated waves, from dredge spoil disposal, or from other tributary streams. The erodible deposits in shallow areas accumulate during periods of storm runoff when river turbidity can be observed to extend over these areas, that is when the mixing zone extends over the shallow areas, as well as depositing from more usual flows as will be described subsequently. When suspended aggregates reach portions of the estuary

having a salinity gradient, the upstream predominance of near-bed currents assures their upstream movement as long as bed shear stress is sufficient to keep them suspended.

The aggregates rapidly accumulate on the bed during each time near slack water that the near-bed currents fall to magnitudes that permit deposition. The burden of the particles deposited last on the aggregates near the bottom of a new deposit will cause the collapse of the lower aggregates' structure when the deposit is more than a few centimeters thick,[11(p.77)] and the shear strength of the deposit will increase with depth. The depth to which the new deposit scours when the currents increase after slack will then depend on the bed shear stress imposed by the flow. If the currents during both flood and ebb are sufficient to scour all of the new deposit, the net movement will be determined approximately by current predominance. However, if the shear stress during ebb is less than sufficient to suspend all of the newly deposited material, there will be a portion of the material resting on the bed during ebb, which will be resuspended and transported during the predominant flood flows. The net rate of upstream movement will be greatly enhanced. The occurrence of this process in Savannah Harbor is shown in figs. 6-14. It is important to recognize the effect of the amount of material deposited during slack periods on this process.

Continuing deposition will occur when the bed shear during flood, as well as during ebb, is insufficient to resuspend all of the material deposited during preceding slack periods. The actual shear necessary depends on the amount of material deposited. This situation would occur immediately downstream from the toe of average salinity intrusion in a uniform channel, where bed shear is lowest, unless the material had already been removed from the flow downchannel. The maximum rate of shoaling in Savannah Harbor, however, occurs near sta 125+500, which is well downstream from the toe. Shoaling there results from the markedly reduced bed shear stresses, relative to those upstream or downstream, resulting from the widened channel together with the large amount of material deposited during each near-slack water period.

A large portion of the sediment moving upstream intermittently in

suspension moves right on through the toe of the salinity intrusion, mixes with the fresh water and its suspended sediment load, and is carried seaward up over the saline intrusion in the large portion of the channel volume having a vertical salinity gradient and higher than normal rates of internal shearing.

The salinity profiles show a lower zone with nearly uniform salinity and a vertical gradient toward lower salinities in the zone above. The boundary between these zones is fuzzy but discernible. This boundary moves upstream and downstream with the tides and has a downward slope in the upstream direction. There is a net upward movement of saline water at this upper boundary because, as the fresher and saline waters mix, the salinity and density decrease. There is continuing displacement of the less saline water by more saline water.

A nearly horizontal lens of high concentrations of suspended sediment on the salinity boundary near the mouth of the Mississippi River, which suffers very little disturbance from tides, is evidence of this phenomenon. Those aggregates moving upstream near the bed or formed at the interface whose settling velocities are comparable to the upward currents are held in this zone of upward moving water as are flocs suspended in a sludge-blanket upflow clarifier. Smaller particles moving through this region are often "caught" by the suspended particles, the suspended particles themselves combine, until the settling velocity exceeds the upflow velocity component and the particles fall through the saline zone to deposit.

The observation of flood predominance near the bed is further evidence of net upflow through the upper fuzzy boundary of saline water. This upward current transports preferentially aggregates having low settling velocities and carries them into the zone where appropriate shearing rates, disperse riverborne particles, and considerable time are available for their growth. They are transported seaward in the upper regions.

When these particles are transported into the broader areas of the estuary where bed shears are often low, or if their settling velocity has increased to exceed the upward component of mixing water, these

aggregates settle into the saline region where they are again transported upstream and continue through the cycle.

The processes described herein are rate-dependent processes. The rates of aggregation are important relative to the time for aggregation to occur. Since material can go through the cycle again and again, probably forming and partially breaking aggregates several times, the available time can be long. The rates that determine whether an estuary with appropriate hydraulic conditions experiences the processes described herein are the relative rates of suspended sediment supply and of sediment loss from the system. When the rate of supply exceeds the rate of loss downstream, say, to the ocean, the concentration in the recycling system will increase until the deposits formed during slack water are thick enough to leave shoal material at the rate sediment is supplied. Sediment brought in by storm flows can deposit in shallow areas when the mixing zone moves down to those areas or when aggregates are transported from the mixing zone to those areas, then can be continually resupplied to the process when resuspended by wind-generated waves. The rate of sediment loss from the system, and hence alleviation of shoaling, can be augmented by disposing of dredge spoil outside the recycling system.

Seaward transport from the system will be enhanced if high concentrations of suspended sediment can be prevented from moving upstream to the extent that the low concentration inhibits aggregation. Every feasible means to minimize the suspended sediment concentration in shoaling areas should be considered.

The recycling processes described herein account for the turbidity maxima observed in estuaries.

VI. METHODS FOR ALLEVIATING SHOALING AT SAVANNAH HARBOR

Extensive field and model studies of Savannah Harbor have already resulted in plans for reducing the cost of maintenance. The methods offered herein are presented to illustrate briefly the application of information obtained during this study.

Keep the Sediment Moving

The importance of bed shear stress to the upstream movement of sediment is evident from the data obtained during this study. If the shear stresses can be made to equal or exceed those that suspend the sediment material during its transport into the shoaling area, the sediment can be kept in motion and increased loss from the recycling system can be obtained by tidal diffusion. Carquinez Strait in the San Francisco Bay system is an example where shoaling does not occur in the channel wherein mixing occurs. The aggregates formed there deposit at unusually high rates in contiguous areas where the bed is protected from shear and where enhanced aggregation rates are provided by flow through piles. Increased bed shear along the entire channel usually cannot be achieved without major works that increase tidal flows, but locally reduced bed shear stresses, such as those in the turning basin in Savannah Harbor, can be increased by making the channel width uniform and by modifying the channel to reduce energy dissipation. The turning basin could be moved up beyond the mixing zone. Channel banks could be made steeper and side-channel shallow areas eliminated. The effects of such channel modifications on bed shear stress can be evaluated with hydraulic models.

Minimize Suspended Sediment Concentrations

The center role of suspended sediment concentration in determining rates of aggregation and shoaling is amply demonstrated. Means for minimizing suspended sediment concentrations include the adherence to "clean" dredging methods and spoiling outside of the area from which sediment can reenter the process. Tributaries that carry large amounts of suspended sediment might be diverted to join the ocean elsewhere if their flows through the harbor are not needed to carry wastes.

Reduce Internal
Shearing Above the Bed

Areas immediately downstream from pile-supported structures shoal rapidly because internal shearing is enhanced in flow around piles and because bed shears are reduced in the region. Large aggregates are formed quickly from small ones at moderate concentrations of suspended sediments. Flow through such pile structures can often be minimized by orienting the structure appropriately and by designing the structure with minimum supporting piles. Internal shearing that results from salinity gradients does not appear amenable to reduction.

The benefits of these methods in individual cases must be compared with their total cost to determine their desirability.

VII. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

This field study in Savannah Harbor, a partially mixed estuary, yielded information leading to the description of sediment transportation and shoaling processes presented in Chapter V. The following conclusions can be drawn from the field data, the discussion of relevant processes, and the description presented in this report:

a. Aggregation processes enhance the settling velocities of suspended particles and determine the physical properties of the sediment bed surface. Aggregation processes are central to the transportation processes leading to the formation of shoals in Savannah Harbor.

b. Repeated collision of suspended cohesive particles resulting from internal shearing in the flow, particularly in the large volume of enhanced internal shearing caused by the salinity gradient in the mixing zone, is the dominant mechanism that produces aggregation.

c. The rate of aggregation depends on the concentration of suspended sediment, very strongly on the heterogeneity of the suspended particle sizes, and on local shearing rate.

d. The sediment moves into the region of high shoaling rates with tidal currents from downstream with the more saline waters near the bed. The material deposits during the periods of low currents near the times of slack water, then is partially or entirely resuspended as the currents increase. Bottom flood predominance is one factor causing net upstream movement of sediment.

e. When the deposit formed during slack periods is more than a few centimeters thick, the weight of the overburden crushes the lower aggregates in the new deposit and thereby enhances their shear strength. The shear strength of such a deposit increases with depth. Under this circumstance, stronger flood currents, which apply greater shear stress to the bed surface, erode the new deposit to a greater depth than do the weaker ebb currents. Some or all of the sediments are suspended and transported by flood currents and rest on the bed during ebb. This process greatly enhances the rate of sediment movement into the shoaling area.

f. Sediment accumulates to form shoals wherever the bed shear stresses during both flood and ebb are insufficient to resuspend all of the material deposited during the preceding slacks. Both the thickness of each deposit, which determines the shear strength profile of the deposit, and the shear stresses applied by the flow determine the shoaling rate in these areas.

g. Some of the aggregated sediment moving upstream near the bed with the more saline water moves through the landward limit of saline water, mixes with the disperse riverborne particles, and is carried seaward over the saline intrusion through the large volume having a vertical salinity gradient and enhanced internal shearing. These returning aggregates greatly increase the rate of aggregation of riverborne suspended particles. Suspended sediment also moves vertically upward from the saline water zone as the saline waters mix with less saline water.

h. Aggregated suspended particles settle downstream and in shallow areas where they reenter the upstream movement, or they rest until resuspended by wind-generated waves and then reenter the upstream movement.

i. Most of the new information obtained during this study was that from the measurements made within 8 ft of the sediment bed surface, and was obtained by accurately positioning the sampling intake and current meter above the sediment bed. It can be concluded that accurate positioning of such equipment relative to the sediment bed surface is very desirable for measurement and sampling of flows in estuaries.

Many interesting features in a natural system as complex as the Savannah Harbor estuary could be studied further. Those areas of further study needed to improve knowledge that would lead to reduced maintenance costs are presented here.

a. The shear stress applied by the flow to the bed is an important factor in the formation of shoals. Our present ability to calculate the shear stress from a velocity profile is limited to those cases where the fluid density is uniform. A means for calculating shear stresses when the velocity profile is affected by a vertical density gradient would be useful for design to achieve the necessary bed scour. In terms of the logarithmic description of velocity profiles we need to know the

relations between density gradients and Karman's constant k at the strength of flow.

b. Quantitative descriptions of the sediment transportation processes are needed to evaluate the benefits of proposed remedial measures on channel and harbor maintenance and to predict changes in suspended sediment concentrations resulting from water inflow modifications and the effects of such changes on water quality and on aquatic biota. The velocity and salinity profiles, together with the transportation mechanisms described, suggest that a two-layer numerical model might represent the hydraulic portion with sufficient accuracy, and that the shear strength profile of the bed might be simply represented. Empirical descriptions of aggregation and deposition obtained from flume studies should be useful, and an accounting procedure might be devised to describe the shoal surface.

c. An estuary is a transition between unidirectional freshwater flow and a tidal ocean. All that transpires in this transition is affected to some extent by conditions at both ends. During the last few years suspended sediment inflows to estuaries have been measured, but almost no information is available on rates of loss of sediment from estuaries. Direct measurements would be very desirable. Indirect calculations using a numerical model together with measurements of sediment concentrations inside the estuary are less desirable but perhaps would be achieved more easily.

d. This study involved only one estuary. Savannah Harbor is a partially mixed estuary and is typical of many; but differences in morphometry, in mineral and organic content of the sediment, in tidal ranges, and in temporal changes in freshwater and sediment inflow provide different conditions. Additional studies of this kind are needed to enlarge our knowledge of estuarial sediment transportation.

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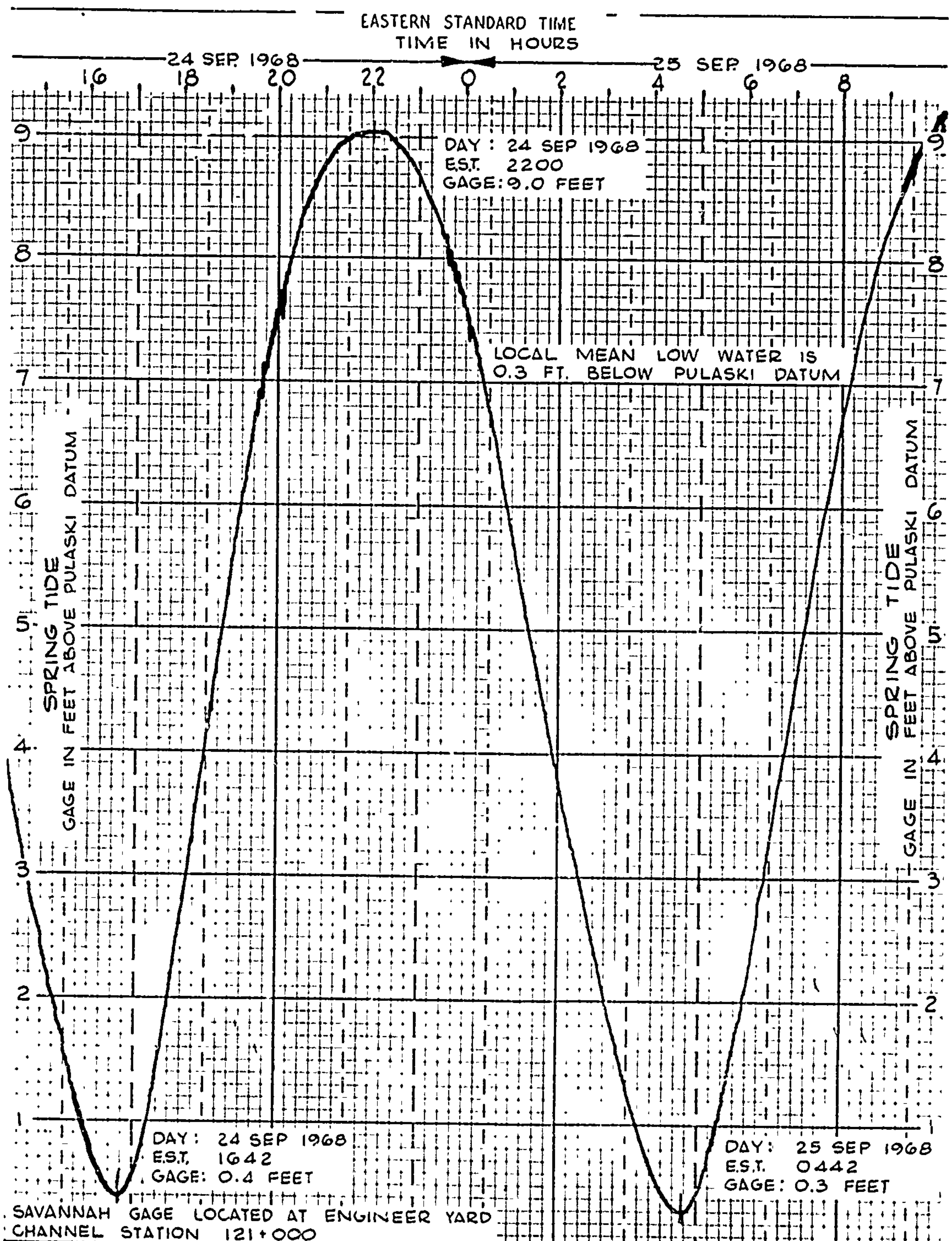
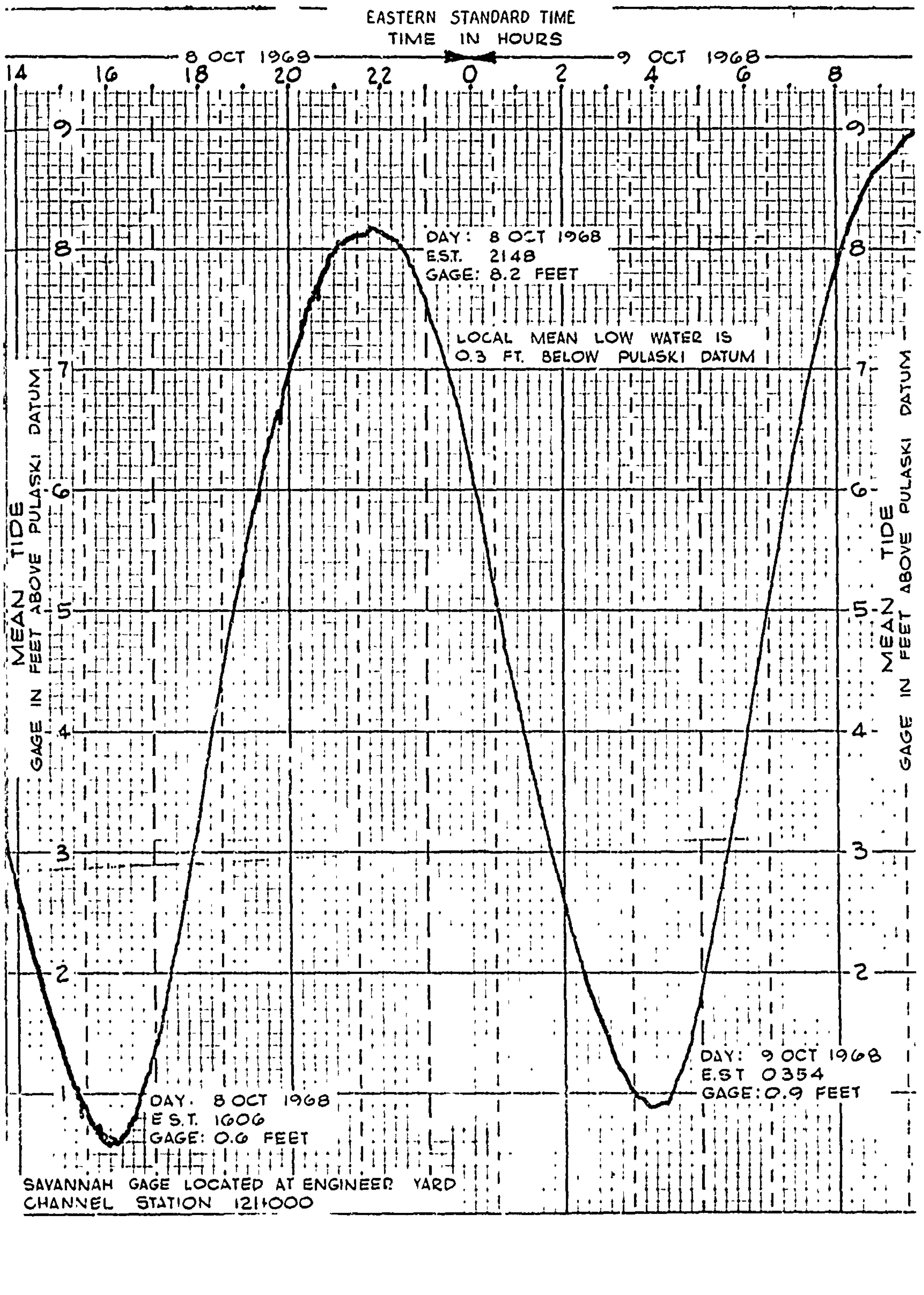
APPENDIX A

FRESHWATER INFLOWS, TIDES, AND WINDS DURING FIELD STUDIES

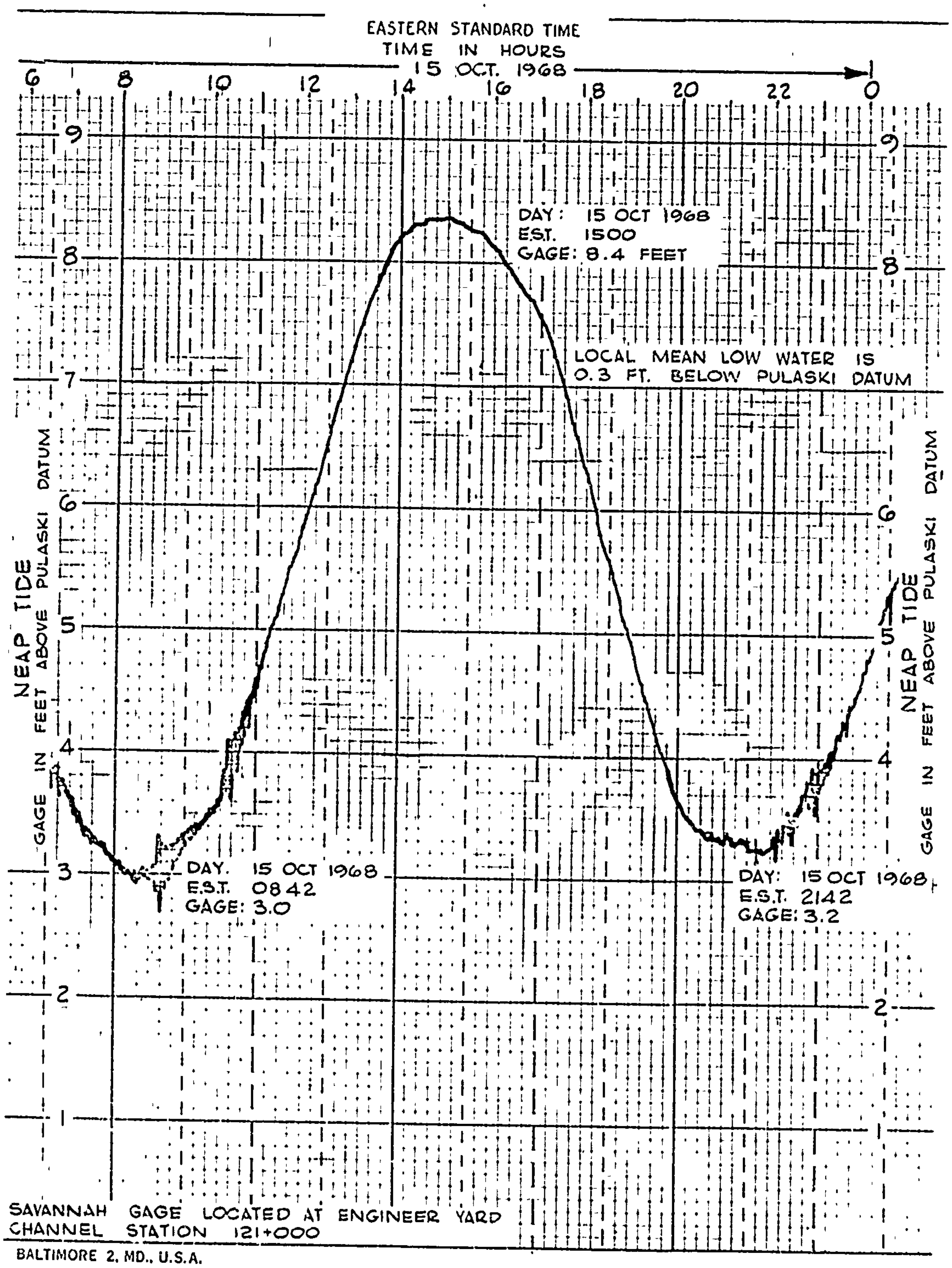

EASTERN STANDARD TIME
TIME IN HOURS
24 SEP 1968
25 SEP 1968
16 18 20 22 0 2 4 6 8
9 8 7 6 5 4 3 2 1
DAY: 24 SEP 1968
E.S.T. 2200
GAGE: 9.0 FEET
LOCAL MEAN LOW WATER IS
0.3 FT. BELOW PULASKI DATUM
SPRING TIDE
GAGE IN FEET ABOVE PULASKI DATUM
DAY: 24 SEP 1968
E.S.T. 1642
GAGE: 0.4 FEET
DAY: 25 SEP 1968
E.S.T. 0442
GAGE: 0.3 FEET
SAVANNAH GAGE LOCATED AT ENGINEER YARD
CHANNEL STATION 121+000

MD., U.S.A.



EASTERN STANDARD TIME
TIME IN HOURS
8 OCT 1968
9 OCT 1968
14
16
18
20
22
0
2
4
6
8
9
8
7
6
5
4
3
2
MEAN TIDE
GAGE IN FEET ABOVE PULASKI DATUM
DAY: 8 OCT 1968
E.S.T. 2148
GAGE: 8.2 FEET
LOCAL MEAN LOW WATER IS
0.3 FT. BELOW PULASKI DATUM
DAY. 8 OCT 1968
E.S.T. 1606
GAGE: 0.6 FEET
DAY: 9 OCT 1968
E.ST 0354
GAGE: 0.9 FEET
SAVANNAH GAGE LOCATED AT ENGINEER YARD
CHANNEL STATION 121+000

A



EASTERN STANDARD TIME
TIME IN HOURS
15 OCT. 1968
6
8
10
12
14
16
18
20
22
0
9
8
7
6
5
4
3
2
1
NEAP TIDE
GAGE IN FEET ABOVE PULASKI DATUM
DAY: 15 OCT 1968
E.S.T. 1500
GAGE: 8.4 FEET
LOCAL MEAN LOW WATER IS
0.3 FT. BELOW PULASKI DATUM
DAY. 15 OCT 1968
E.S.T. 0842
GAGE: 3.0
DAY: 15 OCT 1968
E.S.T. 2142
GAGE: 3.2
SAVANNAH GAGE LOCATED AT ENGINEER YARD
CHANNEL STATION 121+000
BALTIMORE 2, MD., U.S.A.

SAVANNAH HARBOR GAUGE - CHANNEL STATION 121+000

PULASKI DATUM SEPTEMBER 1968

DATE DAY	TIME OF HIGH HOUR	TIME OF LOW HOUR	HEIGHT OF HIGH FEET	HEIGHT OF LOW FEET	DATE DAY	TIME OF HIGH HOUR	TIME OF LOW HOUR	HEIGHT OF HIGH FEET	HEIGHT OF LOW FEET
1.	4.00	10.20	8.50	1.70	16.	4.00	10.00	6.80	2.30
	16.90	23.30	9.30	1.30		16.40	23.10	8.00	3.00
2.	4.80	11.60	8.10	0.50	17.	5.20	11.20	7.30	2.20
	17.60	0.00	9.00	0.00		17.30	0.00	8.20	0.00
3.	6.00	0.60	8.20	0.70	18.	6.20	0.20	7.50	2.40
	18.70	12.40	9.10	0.30		18.30	12.20	8.70	1.70
4.	6.90	1.70	8.40	0.30	19.	6.70	1.20	8.10	2.00
	19.80	13.70	9.20	0.00		19.20	13.10	8.80	1.20
5.	8.00	2.60	8.60	0.00	20.	7.50	1.90	8.20	1.50
	20.80	14.70	9.30	-0.1		20.30	14.20	9.20	0.90
6.	8.80	3.40	8.80	-0.10	21.	8.60	2.80	8.80	1.30
	21.30	15.60	9.10	-0.20		21.10	15.00	9.50	0.90
7.	9.60	4.30	8.70	-0.40	22.	9.70	3.50	9.30	1.60
	22.00	16.30	9.00	-0.20		22.00	16.00	9.60	0.80
8.	10.20	4.80	8.70	-0.20	23.	10.50	4.20	9.50	1.00
	22.60	17.00	8.70	0.10		22.60	16.90	9.40	0.80
9.	11.00	5.20	8.50	0.10	24.	11.00	5.10	9.60	0.50
	23.20	17.70	8.60	0.60		23.00	17.70	9.00	0.40
10.	11.50	5.90	8.50	0.50	25.	11.70	5.70	9.30	0.30
	23.90	18.00	7.90	1.00		23.60	16.40	8.70	0.40
11.	12.10	6.40	7.90	0.10	26.	12.50	6.30	9.00	0.20
	0.00	18.60	0.00	0.50		0.00	19.10	0.00	0.30
12.	0.50	6.70	7.00	0.50	27.	0.60	7.00	8.20	0.20
	13.00	19.10	8.00	1.50		13.30	19.90	8.80	0.70
13.	1.40	7.20	7.00	1.20	28.	1.50	7.80	7.80	0.70
	13.80	19.60	7.70	1.70		14.30	20.70	8.70	1.30
14.	1.70	8.20	6.60	1.70	29.	2.60	8.80	7.80	1.20
	14.50	20.70	7.80	2.40		15.40	21.80	8.80	1.70
15.	3.20	9.00	6.60	1.70	30.	3.70	10.10	7.70	0.70
	15.20	21.40	7.70	2.70		16.30	23.20	8.40	1.10
						728.1	673.00	489.21	53.21

MHW	MLW	H	L	T	HW	LW
8.43	0.92	-159.9	217.0	9.9	8.89	2.97

LOW WATER MEAN FT	LOW WATER LOW FT	LOW WATER HIGH FT	HIGH WATER MEAN FT	HIGH WATER LOW FT	HIGH WATER HIGH FT
0.92	-0.40	3.00	8.43	6.60	9.60

TIDAL RANGE MEAN FT	TIDAL RANGE MIN FT	TIDAL RANGE MAX FT	LUNITIDAL INTERVAL L.W. HOURS	LUNITIDAL INTERVAL H.W. HOURS
7.52	4.1	9.5	2.97	8.89

NOTES:

1. Local mean low water is 0.3 ft. below Pulaski Datum.
2. Time is Eastern Daylight Time.

SAVANNAH GAUGE

PULASKI DATUM OCTOBER 1968 - Channel Station 121+000

DATE DAY	TIME OF HIGH HOUR	TIME OF LOW HOUR	HEIGHT OF HIGH FEET	HEIGHT OF LOW FEET	DATE DAY	TIME OF HIGH HOUR	TIME OF LOW HOUR	HEIGHT OF HIGH FEET	HEIGHT OF LOW FEET
1.	5.00	11.60	7.40	0.40	17.	5.00	11.30	8.10	2.20
	17.40	0.00	8.40	0.00		17.80	0.00	8.80	0.00
2.	5.90	0.50	7.70	0.40	18.	6.20	0.60	8.50	1.90
	18.50	12.60	8.40	0.10		19.10	13.40	8.80	1.40
3.	7.00	1.40	8.10	0.00	19.	7.50	1.60	8.70	0.90
	19.50	13.40	8.50	0.00		19.80	14.20	9.80	1.00
4.	7.70	2.30	7.90	-0.30	20.	8.10	2.20	8.80	0.20
	20.50	14.20	8.70	-0.20		20.30	14.70	9.10	0.20
5.	8.60	2.70	8.90	0.30	21.	8.90	2.90	9.10	-0.30
	21.30	15.20	8.90	1.20		21.10	15.70	9.00	0.10
6.	9.40	3.60	9.00	0.80	22.	10.10	3.50	9.60	0.20
	21.60	16.00	8.90	0.80		21.80	16.60	9.20	0.00
7.	9.80	4.10	8.50	0.30	23.	10.60	4.50	9.60	-0.10
	22.10	16.60	8.40	0.30		22.60	17.40	8.90	0.00
8.	10.30	4.60	8.50	-0.10	24.	11.60	5.20	9.70	-0.20
	22.80	17.10	8.20	0.60		23.70	18.30	8.60	0.30
9.	11.40	4.90	9.10	0.90	25.	12.30	5.80	9.20	-0.10
	23.40	17.60	8.20	1.90		0.90	19.10	0.00	-0.20
10.	11.70	5.60	8.90	1.80	26.	0.40	6.60	7.10	-0.20
	23.90	18.00	8.10	2.10		13.40	19.80	8.80	0.50
11.	12.60	6.20	8.60	1.90	27.	1.60	7.50	7.80	0.60
	0.00	18.60	0.00	2.40		14.20	20.60	8.60	0.80
12.	0.50	6.60	7.60	2.20	28.	2.50	8.70	7.70	0.60
	13.00	17.30	8.20	2.20		15.20	21.90	7.60	0.40
13.	1.40	7.30	7.00	2.10	29.	3.90	10.[illegible]0	7.00	0.40
	13.80	20.00	8.10	2.90		15.80	22.90	8.20	0.70
14.	2.70	8.20	7.00	2.60	30.	4.70	11.20	7.80	0.40
	15.20	20.90	8.40	3.40		17.00	23.90	8.10	1.50
15.	3.40	9.70	7.20	3.00	31.	5.70	12.20	8.00	0.70
	16.00	22.70	8.40	3.20		18.20	0.00	8.20	0.00
16.	4.90	11.00	7.60	2.60					
	16.70	23.80	8.50	2.80					
						756.7	710.80	502.71	56.51

MHW	MLW	H	L	T	HW	LW
8.38	0.96	-107.3	-465.2	63.5	8.97	3.01

LOW WATER MEAN FT	LOW WATER LOW FT	LOW WATER HIGH FT	HIGH WATER MEAN FT	HIGH WATER LOW FT	HIGH WATER HIGH FT
0.96	-0.30	3.40	8.38	7.00	9.70

TIDAL RANGE MEAN FT	TIDAL RANGE MIN FT	TIDAL RANGE MAX FT	LUNITIDAL INTERVAL L.W. HOURS	LUNITIDAL INTERVAL H.W. HOURS
7.42	3.8	9.9	3.01	8.97

Notes:

1. Local mean low water 0.3 ft. below Pulaski Datum.
2. Time is Eastern Daylight Time.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

2-1985.00 SAVANNAH RIVER NEAR CLYO, GA.

USE RT 05

S	DATE	TMAX	MAX	MIN	MEAN	EQ-GH	DATUM	SHIFT	MEAN Q
	9-04	2400	6.03	5.99	5.98	5.99			7390
	9-05	1600	6.12	6.03	6.09	6.09			7510
	9-06	0100	6.12	6.00	6.08	6.08			7490
	9-07	0100	5.99	5.86	5.92	5.92			7310
	9-08	2400	5.98	5.80	5.90	5.90			7280
	9-09	1500	6.10	5.99	6.07	6.07			7480
	9-10	0100	6.08	6.00	6.05	6.05			7460
	9-11	0500	6.01	5.90	5.95	5.95			7350
	9-12	0100	5.90	5.78	5.84	5.84			7220
	9-13	0100	5.78	5.73	5.75	5.75			7120
	9-14	0100	5.73	5.72	5.73	5.73			7100
	9-15	2400	5.86	5.74	5.79	5.79			7160
	9-16	1200	5.90	5.83	5.88	5.88			7260
	9-17	0100	5.82	5.63	5.73	5.73			7110
	9-18	0100	5.63	5.51	5.57	5.57			69[illegible]0
	9-19	2300	5.52	5.49	5.50	5.50			6850
	9-20	1500	5.59	5.53	5.57	5.57			6930
	9-21	2300	5.66	5.58	5.61	5.61			6970
	9-22	1500	5.77	5.68	5.74	5.74			7110
	9-23	0100	5.73	5.44	5.60	5.60			6960
	9-24	0100	5.43	5.25	5.32	5.32			6650
	9-25	0100	5.25	5.22	5.23	5.23			6560
	9-26	2200	5.24	5.21	5.22	5.22			6540
	9-27	2400	5.33	5.24	5.28	5.28			6610
	9-28	2400	5.45	5.33	5.37	5.37			6710
	9-29	2400	5.82	5.47	5.63	5.63			6990
	9-30	1200	5.94	5.83	5.91	5.91			7300
PERIOD			6.12	5.21					

Water data for September 1968.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

2-1985.00 SAVANNAH RIVER NEAR CLYO, GA.

USE RT 05

S	DATE	TMAX	MAX	MIN	MEAN	EQ-GH	DATUM	SHIFT	MEAN Q
	10-01	0100	5.91	5.72	5.82	5.82			7210
	10-02	0100	5.71	5.49	5.61	5.61			6970
	10-03	0100	5.48	5.40	5.43	5.43			6770
	10-04	0100	5.40	5.37	5.39	5.39			6730
	10-05	0100	5.37	5.34	5.35	5.35			6690
	10-06	2200	5.41	5.34	5.38	5.38			6710
	10-07	2400	5.47	5.41	5.43	5.43			6780
	10-08	1700	5.54	5.46	5.49	5.49			6840
	10-09	2200	5.64	5.54	5.60	5.60			6960
	10-10	1900	5.67	5.64	5.65	5.65			7020
	10-11	1700	5.72	5.65	5.68	5.68			7050
	10-12	0100	5.70	5.62	5.67	5.67			7040
	10-13	0100	5.62	5.56	5.58	5.58			6940
	10-14	2100	5.62	5.57	5.60	5.60			6960
	10-15	0200	5.62	5.58	5.60	5.60			6960
	10-16	2400	5.67	5.58	5.60	5.61			6970
	10-17	2300	5.84	5.68	5.77	5.77			7150
	10-18	1600	5.91	5.84	5.89	5.89			7280
	10-19	2300	5.95	5.86	5.91	5.91			7300
	10-20	2400	6.11	5.96	6.02	6.02			7420
	10-21	2400	6.41	6.13	6.26	6.26			7720
	10-22	1500	6.48	6.41	6.45	6.45			7950
	10-23	0100	6.46	6.39	6.43	6.43			7910
PERIOD			6.48	5.34					

Water data for October 1968.

LOCAL CLIMATOLOGICAL DATA

U S DEPARTMENT OF COMMERCE - C. R. SMITH, Secretary

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION -- ENVIRONMENTAL DATA SERVICE

SAVANNAH, GEORGIA
TRAVIS FIELD
OCTOBER 1968

Latitude 32° 08' N Longitude 81° 12' W Elevation (ground) 46 ft. Standard time used EASTERN

Date	Temperature (°F) Maximum	Minimum	Average	Departure from normal	Average dew point	Degree days (Base 65°)	Weather types shown by code 1-9 on dates of occurrence	Snow, Sleet, or Ice on ground at 07AM (In)	Precipitation Total (Water equivalent) (In)	Snow, sleet (In)	Avg station pressure (In) Elev 51 feet m s l	Wind Resultant direction	Resultant speed (m p h)	Average speed (m p h)	Fastest mile Speed (m p h)	Fastest mile Direction	Sunshine Total (Hours and tenths)	Percent of possible	Sky cover (Tenths) Sunrise to sunset	Midnight to midnight	Date
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	88	59	74	1	61	0	1 8	0	0	0	30.06	20	4.1	5.6	12	SE	9.2	78	2	1	1
2	88	59	74	2	62	0	1 8	0	0	0	30.04	20	3.8	5.0	14	S	11.8	100	3	2	2
3	90*	60	75	3	60	0	1 8	0	0	0	30.04	22	5.9	6.6	14	S	10.8	92	5	4	3
4	84	56	70	-1	56	0		0	0	0	30.00	33	4.1	8.6	14	N	10.4	86	7	5	4
5	77	52	65	-6	43	0		0	0	0	30.10	06	10.3	10.8	17	E	10.3	88	5	5	5
6	81	57	69	-2	60	0	8	0	0	0	29.98	12	6.5	9.2	18	SE	4.4	37	10	9	6
7	87	71	79	8	69	0	1 8	0	T	0	29.90	23	5.0	6.3	15	W	9.7	83	9	9	7
8	89	68	79	9	69	0	23 8	0	.90	0	29.98	03	.7	5.3	21	NW	6.1	52	10	9	8
9	77	68	73	3	65	0	1 8	0	T	0	30.03	04	9.7	10.2	17	NE	2.1	18	10	10	9
10	84	66	75	5	64	0	8	0	T	0	30.02	05	8.1	9.4	14	E	7.6	66	9	7	10
11	85	65	75	6	65	0	1 8	0	T	0	30.09	07	10.4	10.9	17	E	10.0	86	7	6	11
12	85	66	76	7	64	0	8	0	T	0	30.15	08	6.4	7.3	19	E	10.5	91	8	7	12
13	82	65	74	5	62	0	8	0	T	0	30.11	07	4.6	5.5	12	E	7.1	61	10	8	13
14	85	62	74	6	61	0		0	0	0	30.08	06	8.7	9.5	15	E	11.5	100	1	1	14
15	83	65	74	6	64	0	8	0	0	0	30.05	05	11.3	11.7	17	NE	7.8	63	8	7	15
16	75	69	72	5	68	0	1 3 8	0	.64	0	29.98	05	8.8	9.1	17	E	0.9	8	10	10	16
17	82	72	77	10	70	0	8	0	.63	0	29.90	09	8.7	9.5	26	SE	3.6	31	10	10	17
18	81	72	77	10	72	0	3 8	0	.41	0	29.84	10	6.9	8.3	17	SE	0.6	5	10	10	18
19	83	72	78	12	71	0	8	0	.09	0	29.72	01	4.6	8.5	17	NW	0.3	3	10	10	19
20	82	58	70	4	59	0		0	0	0	29.88	35	7.1	7.3	12	N	9.2	82	2	4	20
21	79	51	65	-1	50	0		0	0	0	30.01	06	2.7	5.2	11	NE	9.9	89	8	6	21
22	82	51	67	2	55	0		0	0	0	29.95	10	2.6	5.6	11	SE	8.3	74	3	3	22
23	83	59	71	6	62	0	2 8	0	0	0	29.86	18	3.0	4.5	13	SE	5.2	46	9	6	23
24	81	61	71	6	63	0	23 8	0	.86	0	29.79	14	.6	4.2	27	W	2.8	25	9	9	24
25	71	47	59	-5	43	6		0	0	0	29.80	29	9.8	10.2	22	W	10.5	95	2	1	25
26	66	39	53	-11	33	12		0	0	0	30.04	31	7.7	8.6	15	NW	11.1	100	0	0	26
27	71	35	53	-11	38	12		0	0	0	30.09	19	3.6	4.2	12	S	11.1	100	0	0	27
28	74	46	60	-3	39	5		0	0	0	29.81	26	9.5	11.1	26	W	11.0	100	1	1	28
29	63	37	50	-13	33	15		0	0	0	29.92	29	6.0	7.2	14	NW	11.0	100	0	0	29
30	68	35*	52	-11	35	13		0	0	0	30.08	32	3.6	5.2	9	N	10.9	100	0	0	30
31	73	37	55	-7	40	10		0	0	0	30.20	07	1.9	3.6	19	SE	10.9	100	0	0	31
	Sum 2479	Sum 1780				Total 73	Dep 26		Total 3.53	Total 0	For the month: 29.98	05	2.1	7.5	27	W	Total 246.6	% for month	Sum 178	Sum 160	
	Avg 80.0	Avg 57.4	Avg 68.7	Dep 1.5	Avg 57	Season to date Total 73	Dep 26		Dep 0.95						Date: 24		Possible 352.9	70	Avg 5.7	Avg 5.2	

Temperature Number of days: Max ≥ 32: 0; Max ≥ 90: 1; Min ≤ 32: 0; Min ≤ 0: 0

Greatest in 24 hours and dates: Precipitation 1.18, 16-17; Snow, Sleet 0

Greatest depth on ground of snow, sleet or ice and date: 0

* Extreme for the month May be the last of more than one occurrence
- Below zero temperatures or negative departure from normal
T In columns 9, 10 and 11 and in the Hourly Precipitation table indicates an amount too small to measure
\ Heavy fog — visibility ¼ mile or less
‡ ≤ '0' at Alaskan stations
+ Also on an earlier date or dates

HOURLY PRECIPITATION (Liquid in Inches)

Date	A.M. 1	2	3	4	5	6	7	8	9	10	11	12	P.M. 1	2	3	4	5	6	7	8	9	10	11	12	Date
1																									1
2																									2
3																									3
4																									4
5																									5
6																									6
7											T														7
8													T			.57	.03	.18	.07	.05	T				8
9													T	T	T										9
10													T												10
11															T										11
12												T													12
13													T				T								13
14																									14
15																									15
16	.01	T	T		.05	T	.01	.02	T	.02		.01	.09	.04	.06	.01	.13	.03	.04	.08	.03	T	T	.01	16
17	.06	.03	.08	.04	.02	.01	.13	.08	.18	T						T		T	T	T					17
18		.06	.21	T	T	T	T				.11	.03	T		T	T	T								18
19									T	.05	.04	T													19
20																									20
21																									21
22																									22
23																									23
24															.85	.01				T	T	T	T	T	24
25																									25
26																									26
27																									27
28																									28
29																									29
30																									30
31																									31

Data in columns 6, 12, 13, 14, and 15 are based on 8 observations per day at 3-hour intervals. Wind directions are those from which the wind blows. Resultant wind is the vector sum of wind directions and speeds divided by the number of observations. Figures for directions are tens of degrees from true North; i.e., 09 = East, 18 = South, 27 = West, 36 = North, and 00 = Calm. When directions are in tens of degrees in Col. 17, entries in Col. 16 are fastest observed 1-minute speeds. If the * appears in Col. 17, speeds are gusts. Any errors detected will be corrected and changes in summary data will be annotated in the annual Summary, if published.

AVERAGES BY HOURS

										Resultant wind
01	4	29.99	62	59	83	57	5.2	01	2.3
04	5	29.97	60	57	35	56	5.4	35	2.4
07	6	30.00	59	57	85	55	6.4	03	3.5
10	5	30.03	72	64	64	58	8.8	04	3.9
13	6	29.98	77	65	50	56	11.1	06	1.8
16	6	29.95	76	64	52	56	10.9	11	3.3
19	5	29.97	68	62	71	58	6.9	10	2.5
22	4	30.00	64	60	80	58	5.8	04	1.1

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William H Haggard

Director, National Weather Records Center

USCOMM ESSA ASHEVILLE 200

OBSERVATIONS AT 3-HOUR INTERVALS

DAY 01

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	9	4		R	71	70	93	69	06	7
04	10	7	8			70	69	93	68	06	7
07	10	3	1	8	F	71	70	97	70	06	6
10	9	35	4		KH	78	75	88	74	08	8
13	8	65	7			80	77	88	76	36	3
16	10	18	10		RW	77	75	91	74	30	7
19	10	55	15			76	73	85	71	31	3
22	0	UNL	12			72	71	93	70	29	6

DAY 02

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	8	70	10			70	69	97	69	27	3
04	10	5	10			70	69	97	69	28	4
07	10	5	3		FK	70	69	93	68	31	5
10	10	20	6		H	76	71	79	69	29	4
13	8	20	10			82	74	69	71	29	5
16	5	UNL	12			88	74	50	67	30	5
19	9	CIR	12			78	74	85	73	17	6
22	3	UNL	10			73	72	97	72	19	4

DAY 03

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	4		GF	70	69	97	69	00	0
04	0	UNL	6		GF	67	66	97	66	00	0
07	7	UNL	6		GF	66	65	93	64	00	0
10	4	UNL	10			84	74	61	69	36	5
13	5	UNL	12			88	72	45	64	09	4
16	8	UNL	12			90	70	36	58	07	5
19	10	CIR	12			80	73	69	69	17	6
22	8	CIR	8			74	71	87	70	19	3

DAY 04

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	8	UNL	7			72	70	90	69	00	0
04	4	UNL				67	66	93	65	03	0
07	8	70	3		GFK	69	67	90	66	00	0
10	3	UNL	8			83	71	55	65	29	3
13	4	UNL	10			89	73	47	66	29	5
16	7	UNL	10			88	76	55	70	15	10
19	1	UNL	10			80	71	65	67	16	7
22	0	UNL	9			74	71	87	70	00	0

DAY 05

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	1		GFK	69	68	97	68	00	0
04	8	UNL	0		FK	67	67	100	67	00	[illegible]
07	9	UNL	0	1	FK	68	68	100	68	00	[illegible]
10	7	6	3		FK	78	75	88	74	03	3
13	3	UNL	10			87	75	57	70	18	4
16	6	35	10			87	77	63	73	13	5
19	8	150	10			80	74	74	71	13	3
22	1	UNL	12			75	74	96	73	14	3

DAY 06

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	5		GF	73	72	97	72	19	3
04	6	UNL	0	4	F	69	69	100	69	30	3
07	7	120	2		GF	72	71	97	71	22	3
10		120	12			84	77	72	74	27	6
13		30	12			89	78	59	73	30	6
16	10	15	7		TRW	79	75	85	74	03	6
19	10	25	8		T	76	73	87	72	35	7
22	9	CIR	12			74	73	97	73	25	3

DAY 07

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	100	10			75	74	94	73	00	0
04	4	UNL	10			73	72	97	72	00	0
07	10	3	1	8	F	72	71	97	71	01	6
10	9	100	10			78	74	85	73	02	5
13	8	100	12			86	78	70	75	10	5
16	8	100	10			65	78	72	75	11	8
19	4	UNL	7			79	75	85	74	13	6
22	0	UNL	5		GF	75	74	97	74	07	3

DAY 08

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	8	UNL	0		F	72	72	100	72	00	0
04	8	UNL	0	4	F	71	71	100	71	00	0
07	10	1	0	2	F	73	73	100	73	04	5
10	9	3	2	8	FK	79	76	88	75	04	6
13	9	25	12			86	76	63	72	14	6
16	9	CIR	12			84	76	70	73	09	12
19	10	90	10			78	76	91	75	07	6
22	4	100	8			76	75	97	75	12	4

DAY 09

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	20	5		TRW	74	73	97	73	06	3
04	10	[illegible]	7			71	70	97	70	00	0
07	10	20	4		RWFK	71	70	97	70	27	3
10	9	13	10			80	76	82	74	04	5
13	7	28	15			85	76	65	72	09	4
16	5	UNL	15			85	77	70	74	13	14
19	2	UNL	12			77	74	85	72	11	8
22	7	200	10			74	73	94	72	00	0

DAY 10

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	4	UNL	9			72	71	97	71	00	0
04	3	UNL	5		GF	70	69	97	69	00	0
07	10	UNL	4		GFK	69	68	97	68	00	0
10	10	CIR	12			83	76	72	73	31	7
13	10	CIR	12			87	75	57	70	00	0
16	10	40	5		K	84	78	74	75	13	10
19	10	70	2	8	FK	76	72	82	70	12	5
22	10	80	7			79	76	88	75	18	8

DAY 11

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	80	7		R	78	77	94	76	20	6
04	7	100	7			74	73	94	72	22	5
07	1	UNL	4		GF	71	70	97	70	25	4
10	0	UNL	10			82	73	63	68	32	6
13	6	UNL	12			88	72	49	64	26	12
16	10	CIR	10			87	71	49	63	26	12
19	10	CIR	12			79	70	65	66	25	3
22	10	CIR	12			72	68	82	66	22	4

DAY 12

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	6	CIR	10			68	64	81	62	31	3
04	9	CIR	10			64	61	84	59	34	5
07	9	CIR	8			63	61	87	59	01	3
10	10	CIR	6		K	72	65	66	60	05	6
13	10	CIR	5		K	79	68	54	61	00	0
16	9	CIR	8			81	67	47	59	28	6
19	10	CIR	8			73	67	71	63	08	3
22	10	CIR	8			67	64	87	63	00	0

DAY 13

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	CIR	7			63	62	93	61	00	0
04	10	CIR	7			62	61	93	60	35	3
07	10	CIR	4		K	62	60	90	59	01	3
10	10	CIR	5		K	74	65	62	60	04	5
13	9	CIR	8			79	67	50	59	04	7
16	5	UNL	10			81	66	42	56	04	7
19	0	UNL	10			73	65	64	60	05	4
22	0	UNL	8			64	62	87	60	00	0

DAY 14

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	7			59	58	93	57	00	0
04	0	UNL	7			56	55	93	54	34	3
07	0	UNL	7			57	55	90	55	34	3
10	0	UNL	7			78	66	52	59	04	8
13	2	UNL	12			83	67	43	58	15	4
16	2	UNL	12			82	68	46	59	14	6
19	0	UNL	10			75	68	69	64	12	5
22	0	UNL	7			68	65	87	64	00	0

DAY 15

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	7			63	62	93	61	00	0
04	0	UNL	7			60	59	93	58	00	0
07	0	UNL	3		GFK	61	60	93	59	36	4
10	0	UNL	7			80	70	60	65	06	7
13	9	UNL	10			84	69	44	60	09	12
16	9	UNL	8			83	69	48	61	10	12
19	7	UNL	7			74	66	66	62	10	4
22	3	UNL	7			68	63	76	60	09	4

DAY 16

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	3	UNL	5			60	58	87	56	00	0
04	0	UNL	7			60	59	93	56	30	3
07	8	UNL	7			65	63	90	62	04	5
10	9	UNL	12			81	74	72	71	06	9
13	3	[illegible]	12			85	74	59	69	07	8
16	10	CIR	12			83	72	59	67	10	10
19	10	CIR	10			77	72	76	69	09	5
22	8	CIR	10			73	72	93	71	06	6

DAY 17

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	150	7			72	71	97	71	02	4
04	10	150	7			72	71	97	71	04	8
07	10	CIR	6		K	73	72	93	71	06	5
10	10	19	8			79	75	85	74	07	8
13	10	30	15			82	74	67	70	10	12
16	10	120	15			81	73	69	70	10	13
19	10	120	12			77	71	76	68	08	5
22	10	150	12			75	72	85	70	04	8

DAY 18

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	130	10			73	71	90	70	04	4
04	10	130	10			72	71	97	71	03	4
07	10	130	10			71	70	97	70	02	4
10	10	100	10			78	73	79	71	06	6
13	9	30	15			87	76	59	71	08	10
16	9	25	15			83	75	70	72	11	13
19	7	CIR	15			77	74	85	72	09	7
22	6	UNL	12			75	74	94	73	09	5

DAY 19

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	15	8			74	73	97	73	03	5
04	6	25	8			74	73	97	73	03	6
07	9	40	7			74	73	97	73	35	3
10	9	20	12			84	77	72	74	07	10
13	9	23	12			86	77	68	74	08	12
16	10	23	12			81	75	77	73	08	11
19	4	UNL	12			78	74	85	73	08	9
22	0	UNL	12			75	73	90	72	07	7

DAY 20

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	7	32	12			73	72	93	71	05	5
04	0	UNL	5		GF	70	70	100	70	02	5
07	9	2	1	8	F	72	71	97	71	04	9
10	10	14	6		K	81	75	77	73	05	9
13	8	32	12			85	74	59	69	10	12
16	1	UNL	12			85	71	49	64	09	8
19	0	UNL	10			75	70	76	67	09	7
22	0	UNL	10			68	65	87	64	06	5

DAY 21

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	10			68	67	93	66	05	6
04	0	UNL	7			69	68	93	67	04	7
07	0	UNL	8			69	68	93	67	04	9
10	1	UNL	15			82	70	55	64	06	12
13	3	UNL	15			86	69	42	60	05	10
16	0	UNL	15			85	67	36	55	09	9
19	0	UNL	10			73	66	69	62	10	7
22	0	UNL	8			66	63	87	62	05	5

DAY 22

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	8			65	63	90	62	03	6
04	0	UNL	5			61	60	97	60	35	5
07	0	UNL	8			63	62	93	61	04	8
10	7	UNL	15			76	65	56	59	02	12
13	3	UNL	15			83	70	51	63	07	10
16	3	UNL	15			83	71	55	65	07	12
19	9	60	12			76	69	71	66	06	5
22	2	UNL	10			71	68	84	66	06	5

DAY 23

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	10			67	66	93	65	01	5
04	0	UNL	8			68	67	93	66	02	5
07	10	2	1	8	F	68	67	97	67	03	[illegible]
10	6	10	12			80	74	74	71	04	7
13	7	25	15			86	74	55	68	08	10
16	4	UNL	15			83	72	57	66	10	10
19	0	UNL	12			76	69	69	65	09	5
22	0	UNL	10			69	65	84	64	35	3

DAY 24

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	8			66	63	87	62	36	3
04	10	1	0	4	F	65	64	93	63	35	3
07	10	1	0	2	F	67	66	93	65	35	4
10	1	UNL	12			78	71	69	67	05	7
13	7	30	15			85	72	51	65	07	8
16	2	UNL	15			86	70	45	62	11	7
19	1	UNL	12			77	71	74	68	12	6
22	3	UNL	7			72	70	90	69	10	4

DAY 25

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	2	UNL	6		GF	67	65	90	64	00	0
04	7	UNL	0	1	F	65	64	93	63	35	3
07	10	2	0	2	F	67	66	93	65	36	4
10	3	UNL	6		K	81	[illegible]	72	71	09	5
13	7	75	12			83	71	55	65	07	10
16	2	UNL	12			85	71	49	64	10	10
19	7	140	12			76	70	74	67	13	4
22	3	UNL	7			69	66	87	65	24	3

DAY 26

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	5		GF	66	64	90	63	02	3
04	8	UNL	1	8	GFK	66	65	93	64	34	3
07	10	100	3		GFK	68	65	87	64	02	4
10	9	100	5		K	84	74	61	69	10	6
13	9	100	8			85	71	48	63	12	8
16	7	100	10			85	70	46	62	14	11
19	3	100	10			77	71	76	68	10	6
22	9	100	8			76	71	84	69	08	3

DAY 27

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	8	CIR	4		GFK	72	70	90	69	02	4
04	7	UNL	2		GFK	69	68	93	67	36	5
07	8	20	2		GFK	68	66	93	65	36	3
10	4	UNL	3		K	82	73	65	69	05	8
13	6	30	10			85	70	46	62	09	11
16	10	70	5		K	82	73	63	68	02	6
19	5	UNL	5		K	76	71	76	68	10	5
22	2	UNL	4		K	71	68	87	67	03	3

DAY 28

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	[illegible]	UNL	3		GFK	68	66	90	65	01	3
04	10	0	0		FK	68	67	93	66	35	4
07	10	2	0	2	FK	69	68	[illegible]	67	36	4
10	7	120	3		K	80	73	72	70	02	8
13	8	32	8			85	72	51	65	09	9
16	5	80	8			84	71	53	65	10	11
19	7	UNL	7			75	70	79	68	10	6
22	[illegible]	UNL	7			[illegible]	69	93	68	05	5

DAY 29

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	0	UNL	2		GF	68	67	93	66	34	3
04	3	UNL	2		GF	71	70	93	69	04	5
07	5	UNL	1		GFK	71	69	90	68	04	6
10	6	UNL	5		K	82	71	56	65	03	11
13	10	UNL	12			88	69	33	55	07	13
16	10	UNL	12			84	66	32	[illegible]	09	10
19	8	UNL	12			75	65	58	59	09	5
22	8	UNL	10			65	61	61	57	05	[illegible]

DAY 30

Hour	Sky Cover	Ceiling	Visibility	Vis. Fraction	Weather	Dry Bulb	Wet Bulb	Rel. Hum.	Dew Pt.	Wind Dir.	Wind Speed
01	10	140	10			66	62	81	60	06	5
04	5	UNL	7			[illegible]	62	93	61	35	5
07	0	UNL	2	8	GF	63	61	87	59	01	3
10	0	UNL	8			[illegible]	70	53	63	05	[illegible]
13	4	UNL	9			87	68	36	57	09	10
16	0	UNL	8			86	68	37	57	10	10
19	0	UNL	8			75	64	52	56	15	5
22	0	UNL	8			[illegible]	61	76	58	34	[illegible]

REFERENCE NOTES

CEILING COLUMNS
UNL indicates an unlimited ceiling
CIR indicates a cirriform cloud ceiling of unknown height

WEATHER COLUMN
- * Tornado
- T Thunderstorm
- Q Squall
- R Rain
- RW Rain showers
- ZR Freezing rain
- L Drizzle
- ZL Freezing drizzle
- S Snow
- SP Snow pellets
- IC Ice crystals
- SW Snow showers
- SG Snow grains
- E Sleet
- A Hail
- AP Small hail
- F Fog
- IF Ice fog
- GF Ground fog
- BD Blowing dust
- BN Blowing sand
- BS Blowing snow
- BY Blowing spray
- K Smoke
- H Haze
- D Dust

WIND COLUMNS
Directions are those from which the wind blows indicated in tens of degrees from true North i.e. 09 for East, 18 for South, 27 for West. Entry of 00 in the direction column indicates calm.

Speed is expressed in knots; multiply by 1.15 to convert to miles per hour.

ADDITIONAL DATA

Other observational data contained in records on file can be furnished at cost via microfilm or microfiche copies of the original records. Inquiries as to availability and costs should be addressed to:

Director
National Weather Records Center
Federal Building
Asheville, N. C. 28801

LOCAL CLIMATOLOGICAL DATA

U. S. DEPARTMENT OF COMMERCE - C. R. SMITH, Secretary

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION -- ENVIRONMENTAL DATA SERVICE

SAVANNAH, GEORGIA
TRAVIS FIELD
SEPTEMBER 1968

Latitude 32° 08' N Longitude 81° 12' W Elevation (ground) 46 ft. Standard time used: EASTERN

Date	Temperature (°F) Maximum	Minimum	Average	Departure from normal	Average dew point	Degree days (Base 65°)	Weather types shown by code 1-9 on dates of occurrence	Snow, Sleet, or Ice on ground at 07AM (In.)	Precipitation Total (Water equivalent) (In.)	Snow, sleet (In.)	Avg. station pressure (In.) Elev. 51 feet m.s.l.	Wind Resultant direction	Resultant speed (m.p.h.)	Average speed (m.p.h.)	Fastest mile Speed (m.p.h.)	Direction	Sunshine Total (Hours and tenths)	Percent of possible	Sky cover (Tenths) Sunrise to sunset	Midnight to midnight	Date
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	83	70	77	-3	72	0	1 8	0	.17	0	29.85	03	3.5	6.8	12	W	6.4	48	9	8	1
2	88	69	79	-1	70	0	1 8	0	0	0	29.96	27	3.3	5.2	9	W	8.6	67	8	8	2
3	90	65	78	-2	66	0	1	0	0	0	30.01	11	1.1	3.3	8	S	10.4	82	6	6	3
4	90	66	78	-1	67	0	1 8	0	0	0	30.06	18	1.8	3.6	11	S	10.6	83	5	4	4
5	89	67	78	-1	71	0	2 8	0	0	0	30.04	13	2.2	2.9	10	SE	9.1	71	6	5	5
6	93*	68	81	2	72	0	23	0	.06	0	29.99	30	2.6	5.3	17	SW	8.7	69	8	7	6
7	88	71	80	1	73	0	1	0	T	0	29.99	08	3.3	4.8	11	E	8.3	65	8	6	7
8	88	70	79	0	73	0	23 8	0	.01	0	30.00	08	4.6	5.6	14	SE	6.7	53	9	9	8
9	88	71	80	2	72	0	1 3 8	0	.14	0	29.91	10	3.7	5.3	17	SE	10.0	80	7	7	9
10	89	69	79	1	71	0	1 3 8	0	T	0	29.85	15	2.0	4.3	17	NE	8.8	70	10	8	10
11	89	67	78	0	68	0	1	0	T	0	29.89	25	4.3	7.5	16	W	10.7	85	6	6	11
12	83	62	73	-5	61	0	8	0	0	0	29.96	35	2.2	3.7	10	NE	8.6	69	10	9	12
13	83	61	72	-6	59	0	8	0	0	0	29.98	03	3.9	4.2	8	NE	11.0	88	8	6	13
14	85	55*	70	-7	59	0		0	0	0	29.98	08	1.9	4.2	11	E	12.4	100	1	0	14
15	85	59	72	-5	61	0	1 8	0	0	0	30.00	08	5.5	6.2	16	E	11.3	91	5	4	15
16	88	58	73	-4	65	0	8	0	0	0	29.98	07	5.5	6.6	15	E	7.2	58	9	7	16
17	84	72	78	1	71	0	8	0	.10	0	29.99	08	8.3	9.1	18	E	5.8	47	10	10	17
18	88	71	80	4	71	0		0	0	0	29.93	08	6.7	7.6	17	E	7.7	63	9	9	18
19	87	74	81	5	73	0	3	0	T	0	29.96	07	8.3	9.1	20	SE	5.6	45	9	7	19
20	87	66	77	1	69	0	1 8	0	T	0	30.07	07	7.7	8.6	17	E	9.1	75	6	4	20
21	87	63	75	-1	63	0		0	0	0	30.10	06	8.8	9.4	15	E	12.2	100	1	0	21
22	85	61	73	-3	63	0		0	0	0	30.09	05	8.3	9.1	16	NE	10.6	87	3	2	22
23	87	66	77	2	67	0	1	0	0	0	30.04	06	6.1	7.5	16	NE	9.4	78	6	4	23
24	87	65	76	1	65	0	2	0	0	0	29.99	07	4.2	6.0	12	E	9.3	77	5	4	24
25	88	65	77	2	66	0	2 8	0	0	0	29.93	09	3.6	5.6	14	E	7.6	63	5	5	25
26	87	64	76	1	65	0	2 8	0	0	0	29.88	10	4.0	6.3	13	S	9.5	79	8	8	26
27	86	68	77	3	67	0	1 3 8	0	T	0	29.85	05	5.2	6.5	15	E	6.9	57	6	6	27
28	86	66	76	2	67	0	2	0	T	0	29.94	06	5.3	7.2	15	E	9.9	82	6	5	28
29	88	64	76	2	62	0	1 8	0	0	0	30.07	07	7.4	8.2	17	NE	10.4	87	8	6	29
30	88	61	75	2	59	0	1 8	0	0	0	30.13	07	4.3	6.6	11	E	11.9	100	1	2	30
	Sum 2614	Sum 1974				Total 0	Dep. 0		Total .48	Total 0	For the month 29.98	07	3.5	6.2	20	SE	Total 276.7	% for month	Sum 198	Sum 172	
	Avg. 87.1	Avg. 65.8	Avg. 76.5	Dep. -0.8	Avg. 67	Season to date Total 0	Dep. 0		Dep. -6.77						Date 19		Possible 370.9	74	Avg. 6.6	Avg. 5.7	

Temperature: Number of days — Max ≥ 90°; Max ≤ 32°; Min ≤ 32°; Min ≤ 0°: 0 | 3 | 0 | 0

Greatest in 24 hours and dates — Precipitation: .29 31-1; Snow, Sleet: 0

Greatest depth on ground of snow, sleet or ice and date: 0

* Extreme for the month - May be the last of more than one occurrence
- Below zero temperatures or negative departure from normal
T In columns 9, 10, and 11 and in the Hourly Precipitation table indicates an amount too small to measure
X Heavy fog — visibility ¼ mile or less
‡ ≤ -20° at Alaskan stations
• Also on an earlier date or dates

HOURLY PRECIPITATION (Liquid in Inches)

Date	A.M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	P.M. Hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	Date
1	T	T				.02	.01					T	.01	.05	.07	.01	T								1
2																									2
3																									3
4																									4
5																									5
6															.04	.02	T		T						6
7															T	T									7
8																				T	.01	T			8
9	.10	.01					.02	.01																	9
10																	T	T							10
11	T	T																							11
12																									12
13																									13
14																									14
15																									15
16																									16
17								.10												T	T			T	17
18																									18
19		T	T		T	T					T	T	T												19
20											T	T													20
21																									21
22																									22
23																									23
24																									24
25																									25
26																									26
27												T	T												27
28														T											28
29																									29
30																									30

Data in columns 6, 12, 13, 14, and 15 are based on 8 observations per day at 3-hour intervals. Wind directions are those from which the wind blows. Resultant wind is the vector sum of wind directions and speeds divided by the number of observations. Figures for directions are tens of degrees from true North, i.e., 09 = East, 18 = South, 27 = West, 36 = North, and 00 = Calm. When directions are in tens of degrees in Col. 17, entries in Col. 16 are fastest observed 1-minute speeds. If the 7 appears in Col. 17, speeds are gusts. Any errors detected will be corrected and changes in summary data will be annotated in the annual Summary if published.

Subscription Price: Local Climatological Data $1.00 per year including annual Summary if published. Single copy: 10 cents for monthly Summary, 15 cents for annual Summary. Checks or money orders should be made payable and remittances and correspondence should be sent to the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402.

I certify that this is an official publication of the Environmental Science Services Administration, and is compiled from records on file at the National Weather Records Center, Asheville, North Carolina 28801.

William H. Haggard

Director, National Weather Records Center

AVERAGES BY HOURS

Hour (Local time)	Sky cover (tenths)	Station pressure (In.)	Air temperature	Wet bulb	Relative humidity %	Dew point	Wind speed (m.p.h.)	Resultant wind Direction	Speed (m.p.h.)
01	5	29.97	69	68	92	67	3.1	03	2.0
04	6	29.96	67	67	95	66	3.9	01	2.9
07	7	29.99	68	67	94	66	4.7	02	3.6
10	6	30.02	80	72	70	69	7.9	04	6.0
13	7	29.99	85	73	55	66	8.8	08	6.0
16	7	29.95	84	72	56	66	10.6	10	7.2
19	6	29.96	76	71	75	68	6.3	10	4.7
22	4	30.00	72	69	88	68	4.3	08	1.9

USCOMM ESSA ASHEVILLE 200

OBSERVATIONS AT 3-HOUR INTERVALS

DAY 01

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	8			63	59	81	57	00	0
04	0	UNL	8			61	58	84	56	27	3
07	0	UNL	6		GF	60	57	84	55	32	3
10	0	UNL	6		K	80	70	60	65	23	5
13	5	UNL	9			86	69	42	60	21	7
16	3	UNL	10			83	71	53	64	16	10
19	1	UNL	8			75	68	69	64	17	8
22	3	UNL	8			70	67	87	66	21	3

DAY 02

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	5		GF	68	66	90	65	00	0
04	0	UNL	6		GF	63	62	93	61	00	0
07	2	UNL	0	8	GF	60	58	90	57	00	0
10	0	UNL	8			81	69	53	62	27	6
13	8	40	10			85	69	43	60	25	5
16	6	UNL	10			85	71	48	63	17	12
19	0	UNL	10			75	67	66	63	17	7
22	0	UNL	10			70	66	81	64	18	5

DAY 03

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	7			68	65	87	64	24	3
04	0	UNL	5		GF	63	61	90	60	00	0
07	0	UNL	2	8	GF	62	60	90	59	27	3
10	0	UNL	10			78	68	60	63	24	8
13	7	UNL	12			87	66	31	53	23	7
16	9	UNL	15			88	67	30	53	22	7
19	9	CIR	12			77	69	67	65	18	10
22	5	UNL	8			73	68	79	66	20	8

DAY 04

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	5	UNL	7			70	67	84	65	21	7
04	10	120	10			70	66	79	63	23	0
07	5	UNL	7			67	64	87	63	27	6
10	8	UNL	12			78	68	60	63	01	10
13	10	CIR	12			83	65	36	53	34	10
16	8	CIR	15			82	62	29	47	33	8
19	0	UNL	15			69	58	49	49	03	6
22	1	UNL	12			62	53	52	44	04	5

DAY 05

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	15			58	50	55	42	05	8
04	4	UNL	12			55	46	51	37	03	8
07	4	UNL	12			52	43	49	33	04	10
10	5	UNL	15			67	53	36	39	07	13
13	3	UNL	15			74	59	40	48	08	12
16	5	UNL	15			74	59	40	48	08	10
19	8	CIR	15			65	56	56	49	08	7
22	10	UNL	12			61	55	67	50	07	7

DAY 06

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	8	UNL	12			59	55	75	51	05	5
04	7	UNL	8			58	55	84	53	04	5
07	10	100	5		K	58	55	84	53	05	6
10	10	65	8			74	66	64	61	10	10
13	10	35	10			79	67	50	59	15	13
16	10	140	10			78	68	58	62	13	12
19	10	140	10			76	70	74	67	14	6
22	10	40	10			76	72	82	70	19	7

DAY 07

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	10	10			72	69	87	68	25	3
04	10	4	2		GF	71	69	90	68	24	6
07	10	35	2		GF	72	70	90	69	22	3
10	10	CIR	8			82	73	65	69	25	7
13	10	CIR	15			83	73	61	68	28	9
16	9	35	12			85	73	57	68	20	5
19	2	UNL	12			76	73	85	71	18	6
22	5	UNL	8			73	71	90	70	17	5

DAY 08

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	10	1	8	F	73	71	90	70	08	3
04	5	UNL	0	4	GF	71	70	93	69	26	4
07	10	CIR	0	2	GF	69	68	93	67	07	3
10	10	100	5		K	81	73	69	70	27	3
13	9	CIR	7			85	74	59	69	15	6
16	10	20	10			72	69	87	68	09	5
19	10	100	6		TRW	69	68	93	67	30	7
22	10	6	1	8	F	71	69	90	68	01	5

DAY 09

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	3	0	8	F	68	67	93	66	36	7
04	10	4	1		F	68	66	90	65	02	7
07	10	7	1	8	F	69	66	87	65	03	9
10	10	15	2	8	K	73	68	76	65	06	12
13	10	15	3		RK	73	68	76	65	05	9
16	10	17	4		KH	75	69	74	66	05	10
19	10	17	6		KH	72	67	79	65	05	9
22	4	UNL	7			69	66	84	64	04	8

DAY 10

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	40	7			68	65	84	63	02	7
04	9	45	7			66	63	87	62	36	7
07	10	7	7			67	64	84	62	03	9
10	10	10	4		K	[illegible]	68	76	65	04	9
13	9	25	12			81	71	60	66	06	10
16	7	[illegible]	12			80	71	62	66	10	11
19	3	UNL	12			72	67	79	65	07	6
22	0	UNL	12			69	66	87	65	04	6

DAY 11

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	10			66	64	90	63	04	6
04	8	20	5		F	66	64	90	63	04	7
07	10	3	1		F	66	64	90	63	04	7
10	3	UNL	10			77	70	69	66	06	9
13	7	35	15			84	71	51	64	07	13
16	6	30	15			79	71	67	67	09	14
19	6	15	15			72	68	82	66	08	11
22	4	UNL	12			69	67	90	66	07	7

DAY 12

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	50	12			71	67	81	65	09	5
04	10	50	12			70	66	81	64	05	5
07	10	80	10			68	65	87	64	03	5
10	10	80	6		K	78	70	67	66	07	8
13	9	100	15			80	68	54	62	11	9
16	6	100	15			81	69	53	62	11	11
19	1	UNL	15			73	67	71	63	08	5
22	0	UNL	10			68	65	87	64	03	3

DAY 13

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	9	100	8			66	63	87	62	04	4
04	10	110	8			67	65	90	64	04	3
07	10	110	5		K	68	65	87	64	05	5
10	9	120	4		K	77	70	71	67	06	8
13	10	100	10			79	67	52	60	11	7
16	9	CIR	12			82	68	47	60	14	3
19	4	UNL	10			71	64	66	59	10	4
22	3	UNL	10			67	64	84	62	05	4

DAY 14

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	2	UNL	10			65	63	87	61	03	4
04	1	UNL	10			64	62	90	61	02	6
07	0	UNL	10			64	62	87	60	02	7
10	0	UNL	12			77	68	62	63	05	12
13	2	UNL	15			84	68	41	58	06	12
16	0	UNL	12			82	67	44	58	09	12
19	0	UNL	12			73	66	69	62	08	7
22	0	UNL	12			68	64	81	62	06	6

DAY 15

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	10			66	63	87	62	03	7
04	0	UNL	10			65	63	90	62	03	8
07	10	4	5		KH	66	64	90	63	03	10
10	6	14	12			75	68	69	64	05	12
13	8	35	15			79	70	62	65	05	13
16	9	45	12			78	70	64	65	07	13
19	9	100	12			74	68	74	65	06	11
22	4	UNL	12			72	68	82	66	06	7

DAY 16

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	30	7		R	70	67	87	65	03	9
04	10	4	6		F	70	67	87	66	04	8
07	9	6	5		FK	71	68	87	67	07	9
10	9	100	7			74	71	87	70	06	8
13	10	100	3		R	73	71	90	70	06	10
16	10	20	3		RWK	74	71	87	70	05	7
19	10	15	5		K	72	69	87	68	05	6
22	10	90	4		RK	72	70	90	69	04	6

DAY 17

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	90	6		RK	73	70	87	69	08	7
04	10	25	4		RK	73	70	87	69	05	6
07	10	14	1	8	RK	74	71	87	70	08	12
10	10	15	3		K	76	73	85	71	11	10
13	10	12	8			79	73	74	70	12	12
16	10	40	8			74	71	84	69	10	7
19	10	14	6		R	74	71	87	70	07	7
22	10	110	5		K	73	71	90	70	05	5

DAY 18

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	28	5		K	73	71	90	70	03	6
04	10	40	6		RK	72	71	93	70	04	4
07	10	40	4		K	73	71	90	70	07	6
10	10	8	4		RK	80	76	82	74	10	9
13	10	7	7			80	76	82	74	12	10
16	10	13	8			79	75	82	73	13	9
19	10	23	8			77	74	85	72	13	7
22	10	19	8			76	73	85	71	17	7

DAY 19

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	10	10	8			75	73	90	72	11	3
04	8	UNL	8			75	73	93	72	09	5
07	10	120	3		K	76	74	90	73	09	11
10	10	20	2	8	RK	75	72	87	71	04	5
13	10	12	15			78	74	85	73	34	10
16	10	70	15			79	73	77	71	34	10
19	9	70	15			74	70	82	68	33	9
22	10	9	15			73	70	87	69	29	6

DAY 20

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	7	15	12			70	67	84	65	34	6
04	10	11	12			69	66	84	64	31	6
07	0	UNL	12			63	60	84	58	36	5
10	0	UNL	15			73	63	57	57	36	10
13	2	UNL	15			79	67	50	59	35	10
16	5	UNL	15			80	65	44	56	34	8
19	7	UNL	15			71	64	66	59	35	3
22	1	UNL	15			64	59	75	56	35	3

DAY 21

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	12			58	56	87	54	31	3
04	0	UNL	12			53	51	90	50	27	3
07	3	UNL	10			51	49	90	48	35	3
10	8	UNL	15			72	60	48	51	05	8
13	9	UNL	15			77	59	32	45	07	8
16	10	CIR	15			77	59	32	45	10	8
19	9	UNL	12			66	59	65	54	16	3
22	8	UNL	10			60	57	84	55	00	0

DAY 22

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	4	UNL	7			55	53	86	51	33	3
04	4	UNL	7			52	50	86	48	01	3
07	0	UNL	7			53	51	86	49	01	4
10	0	UNL	10			75	64	52	56	06	7
13	7	45	12			79	66	49	58	15	6
16	5	UNL	15			78	66	52	59	16	9
19	3	UNL	12			70	66	71	60	11	4
22	2	UNL	12			66	62	81	60	14	3

DAY 23

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	4	UNL	10			64	62	87	60	00	0
04	0	UNL	10			59	57	90	56	30	3
07	9	UNL	0	1	GFK	59	58	93	57	00	0
10	10	CIR	6		K	74	68	74	65	24	4
13	7	CIR	12			82	69	51	62	19	6
16	9	30	10			78	68	58	62	18	11
19	8	CIR	10			72	67	79	65	12	4
22	7	UNL	8			69	67	90	66	19	3

DAY 24

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	4	UNL	0	1	GFK	63	62	93	61	35	3
04	8	UNL	0	1	FK	62	61	97	61	32	3
07	10	2	0	8	FK	63	62	93	61	10	3
10	10	4	1		FK	[illegible]	66	90	65	00	0
13	7	80	2	8	TK	73	70	65	66	14	4
16	10	70	7			70	66	81	64	16	6
19	10	110	7			67	65	90	64	00	0
22	10	110	12			65	61	78	58	31	6

DAY 25

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	3	UNL	12			59	56	84	54	32	6
04	0	UNL	12			55	52	80	49	28	5
07	6	120	12			53	50	83	48	28	5
10	0	UNL	15			63	55	60	49	27	7
13	3	UNL	15			69	55	38	42	29	16
16	2	UNL	15			68	52	32	37	27	13
19	1	UNL	15			57	47	44	35	28	7
22	0	UNL	15			51	42	45	30	31	12

DAY 26

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	12			46	40	58	32	29	10
04	0	UNL	12			43	38	65	32	27	8
07	0	UNL	15			39	36	76	32	30	5
10	0	UNL	15			54	44	43	32	35	8
13	0	UNL	15			62	48	32	32	33	12
16	0	UNL	15			65	48	26	29	34	10
19	0	UNL	15			50	44	64	38	28	4
22	0	UNL	12			43	41	86	39	26	3

DAY 27

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	12			40	38	82	35	00	0
04	0	UNL	10			38	36	82	33	00	0
07	0	UNL	12			36	34	82	31	00	0
10	0	UNL	13			59	48	44	37	27	3
13	0	UNL	15			65	51	25	32	19	8
16	0	UNL	15			69	54	35	40	16	9
19	0	UNL	15			56	51	69	46	18	5
22	0	UNL	12			52	49	83	47	20	4

DAY 28

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	12			50	47	83	45	19	5
04	0	UNL	12			47	45	89	44	24	5
07	3	UNL	12			48	45	77	41	20	8
10	0	UNL	12			64	55	54	47	26	12
13	0	UNL	15			73	56	33	42	26	19
16	0	UNL	15			71	51	21	29	27	16
19	0	UNL	15			58	46	31	31	31	6
22	0	UNL	15			50	42	50	32	29	6

DAY 29

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	15			46	40	58	32	29	6
04	0	UNL	15			41	37	70	32	27	6
07	0	UNL	15			37	35	79	31	29	5
10	0	UNL	15			52	43	47	32	36	4
13	0	UNL	15			60	47	35	32	30	10
16	0	UNL	15			62	48	34	32	30	11
19	0	UNL	15			49	44	66	38	28	4
22	0	UNL	15			42	40	83	37	25	4

DAY 30

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	15			41	38	76	34	22	3
04	0	UNL	13			37	35	85	33	26	3
07	0	UNL	12			35	33	85	31	32	4
10	0	UNL	15			53	45	55	37	33	5
13	0	UNL	15			63	50	30	33	30	7
16	0	UNL	15			68	51	27	33	34	8
19	0	UNL	15			53	47	64	41	30	3
22	[illegible]					44	42	86	38	34	3

DAY 31

Hour	Sky cover (tenths)	Ceiling (hds. of ft.)	Visibility whole miles	Visibility 16ths mi	Weather	Dry bulb (F)	Wet bulb (F)	Rel hum (%)	Dew pt (F)	Wind dir	Wind speed (knots)
01	0	UNL	12			41	39	82	36	00	0
04	0	UNL	10			39	36	86	34	00	0
07	2	UNL	7			38	36	82	33	34	4
10	0	UNL	10			64	54	48	44	05	5
13	0	UNL	12			71	53	28	36	02	5
16	0	UNL	8			71	56	37	43	11	7
19	0	UNL	8			58	52	67	47	16	4
22	0	UNL	8			51	48	83	46	00	0

SAVANNAH GEORGIA   68 10

REFERENCE NOTES

CEILING COLUMN

UNL indicates an unlimited ceiling

CIR indicates a cirriform cloud ceiling of unknown height

WEATHER COLUMN

- * Tornado
- T Thunderstorm
- Q Squall
- R Rain
- RW Rain showers
- ZR Freezing rain
- L Drizzle
- ZL Freezing drizzle
- S Snow
- SP Snow pellets
- IC Ice crystals
- SW Snow showers
- SG Snow grains
- E Sleet
- A Hail
- AP Small hail
- F Fog
- IF Ice fog
- GF Ground fog
- BD Blowing dust
- BN Blowing sand
- BS Blowing snow
- BY Blowing spray
- K Smoke
- H Haze
- D Dust

WIND COLUMNS

Directions are those from which the wind blows indicated in tens of degrees from true North, i.e. 09 for East, 18 for South, 27 for West. Entry of 00 in the direction column indicates calm.

Speed is expressed in knots; multiply by 1.15 to convert to miles per hour.

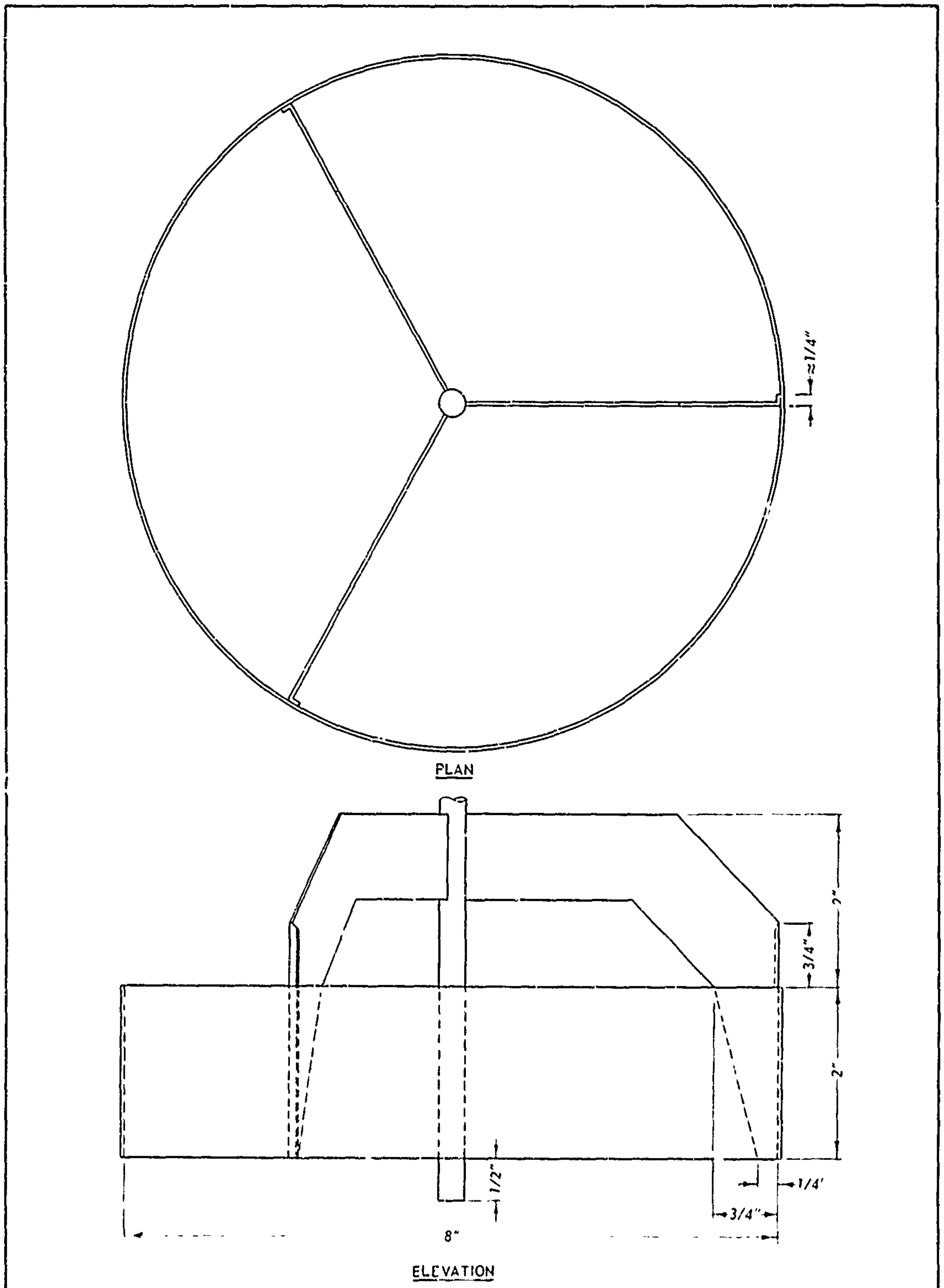
ADDITIONAL DATA

Other observational data contained in records on file can be furnished at cost via microfilm or microfiche copies of the original records. Inquiries as to availability and costs should be addressed to:

Director
National Weather Records Center
Federal Building
Asheville, N. C. 28801

APPENDIX B

CONSTRUCTION SKETCHES OF BOTTOM SENSOR



PROTECTIVE SHIELD

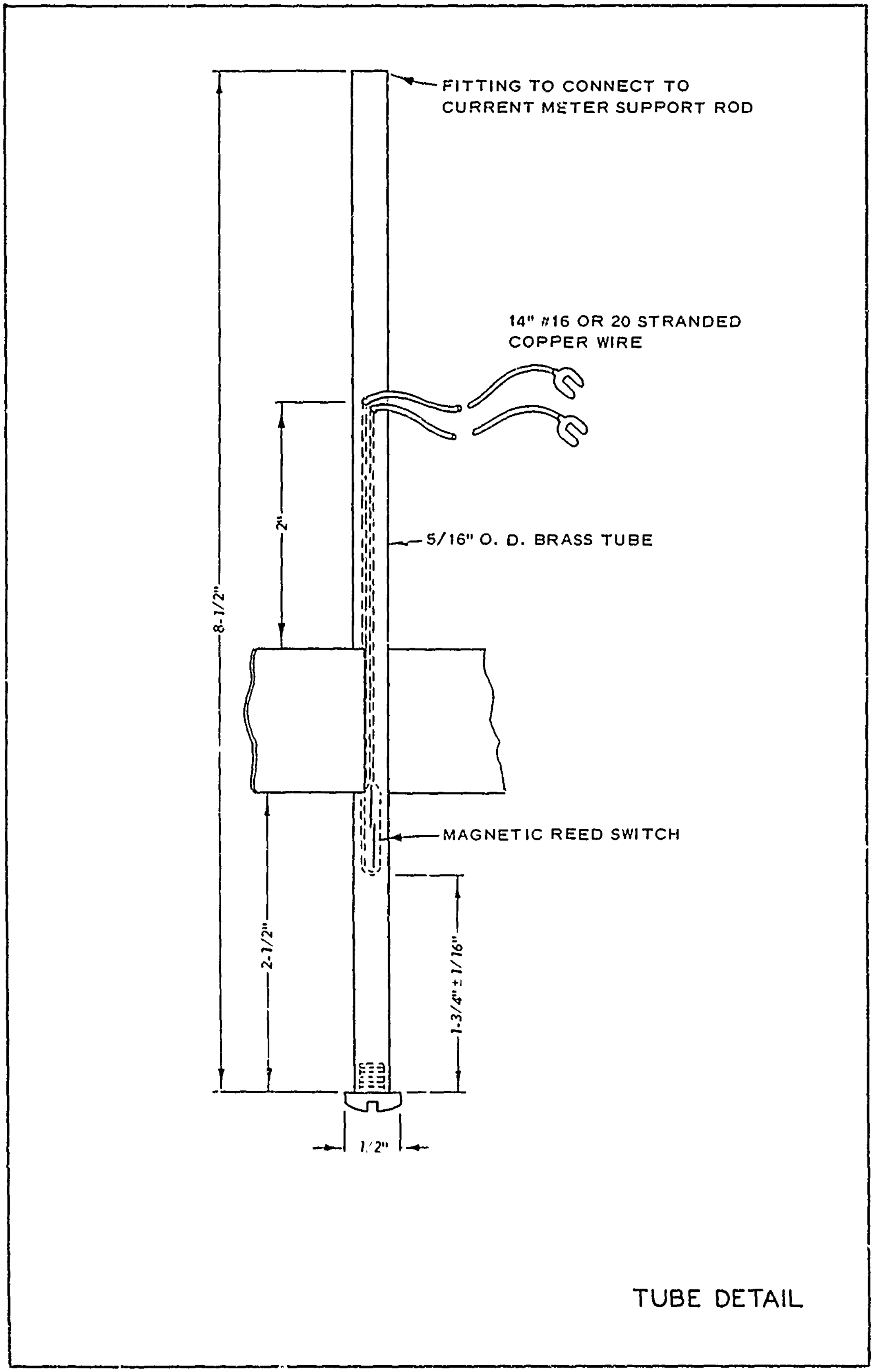
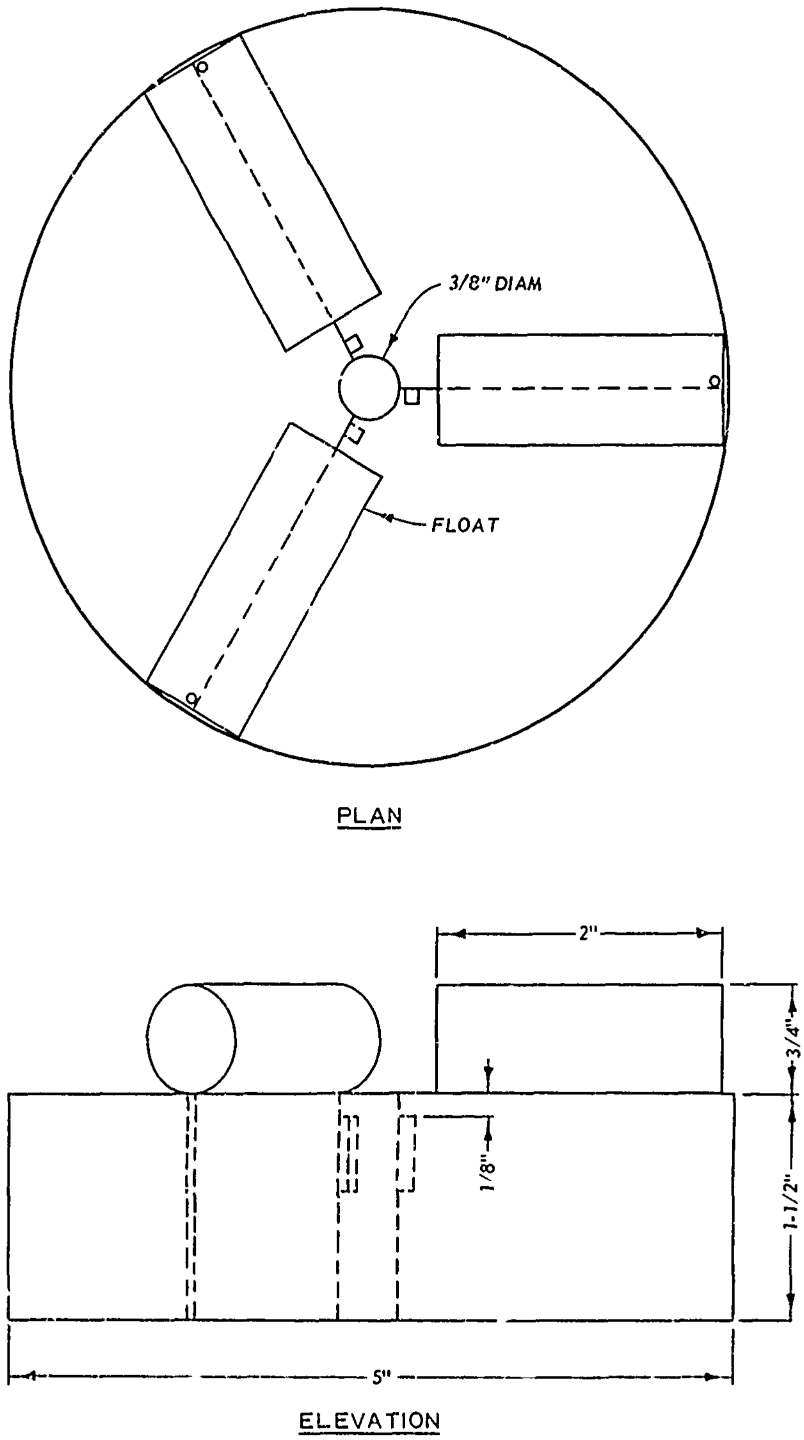

FITTING TO CONNECT TO
CURRENT METER SUPPORT ROD
14" #16 OR 20 STRANDED
COPPER WIRE
2"
5/16" O. D. BRASS TUBE
8-1/2"
MAGNETIC REED SWITCH
2-1/2"
1-3/4" ± 1/16"
1/2"
TUBE DETAIL

PLATE B2



SHEAR SENSOR

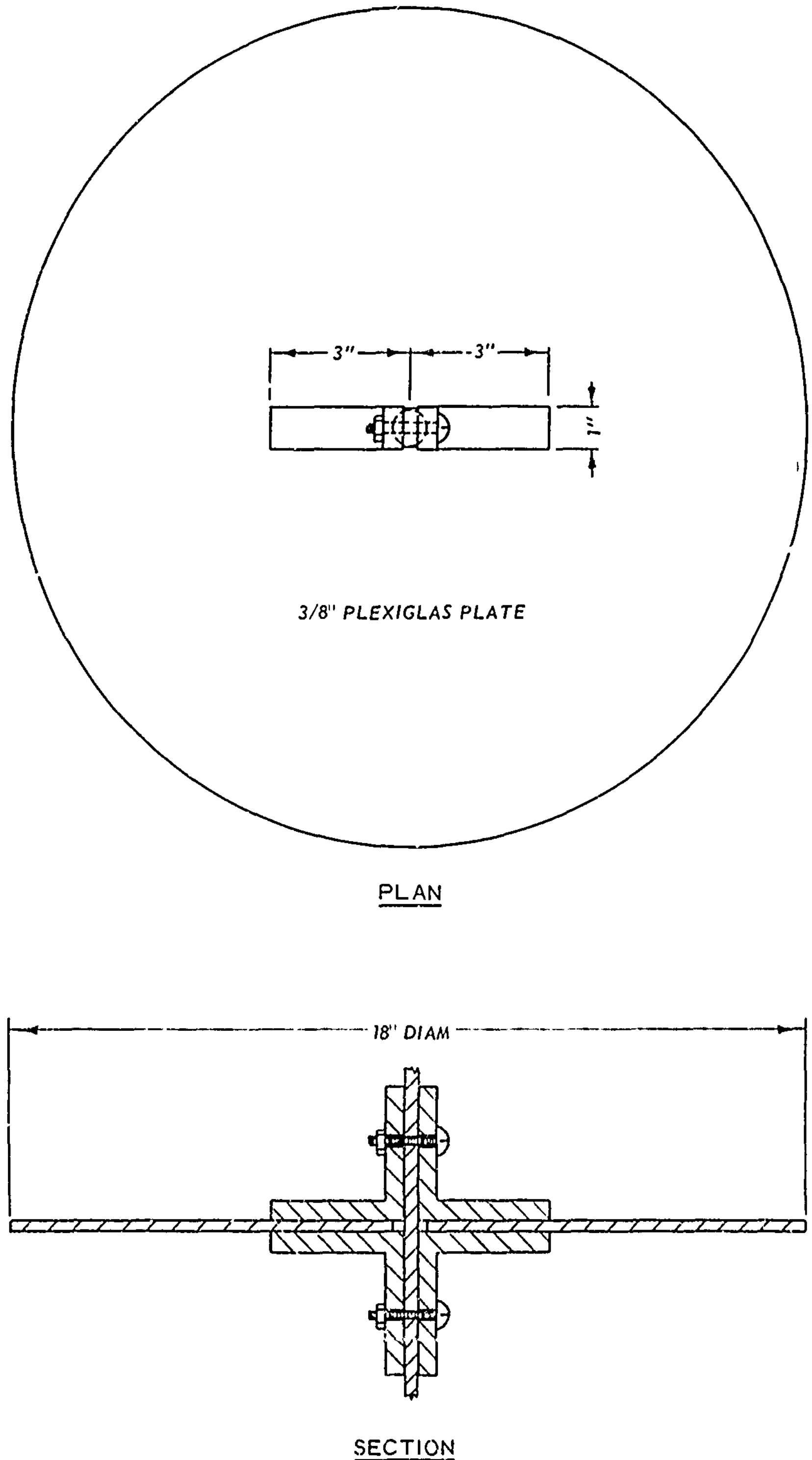
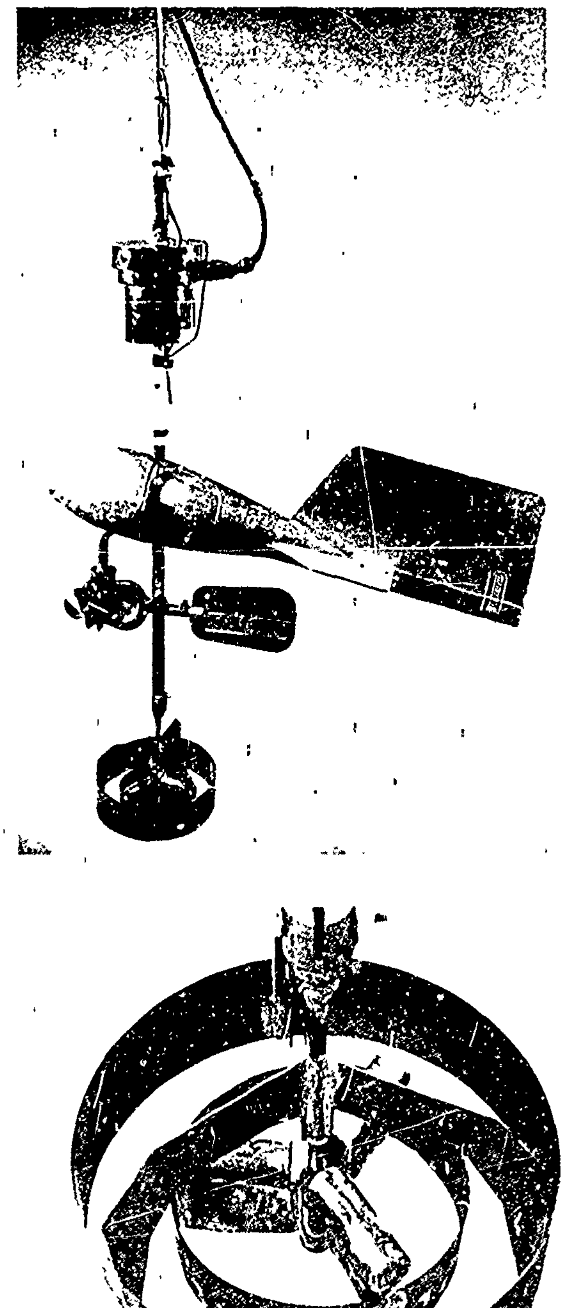
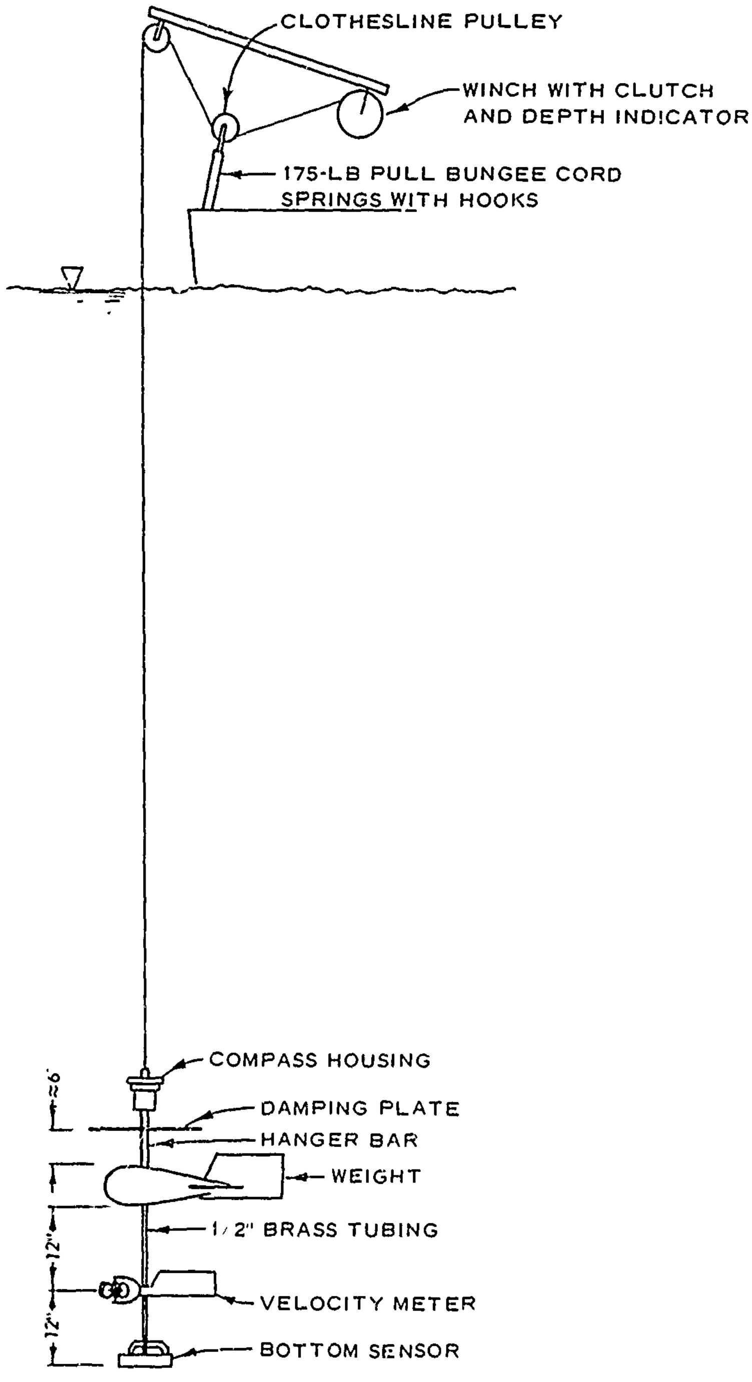


PLATE FOR DAMPING
VERTICAL MOTION

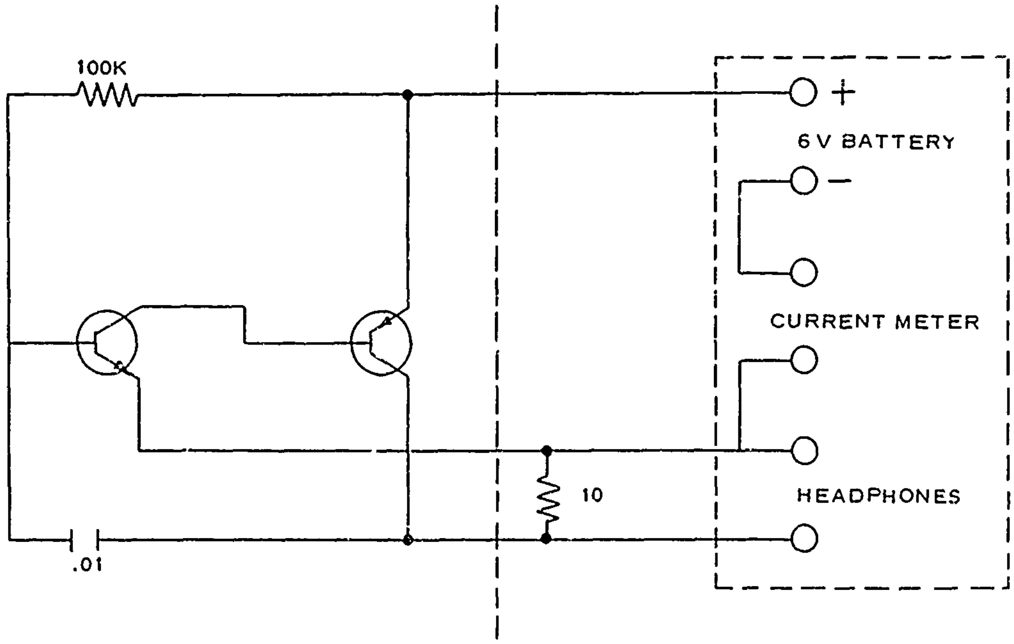
PLATE B4



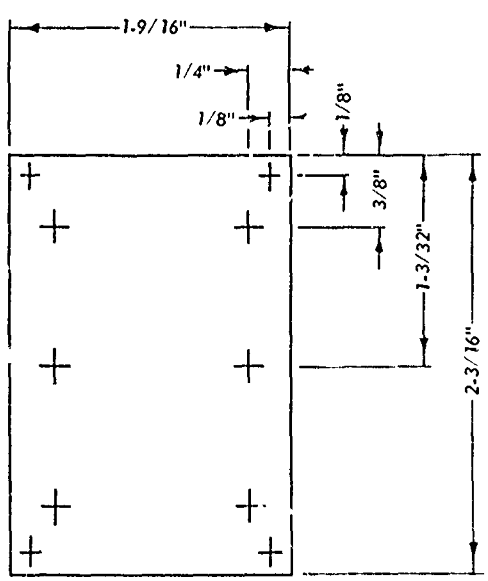
PHOTOS OF INSTRUMENT ASSEMBLY (TOP) AND SHEAR SENSOR (BOTTOM)



INSTRUMENT ASSEMBLY

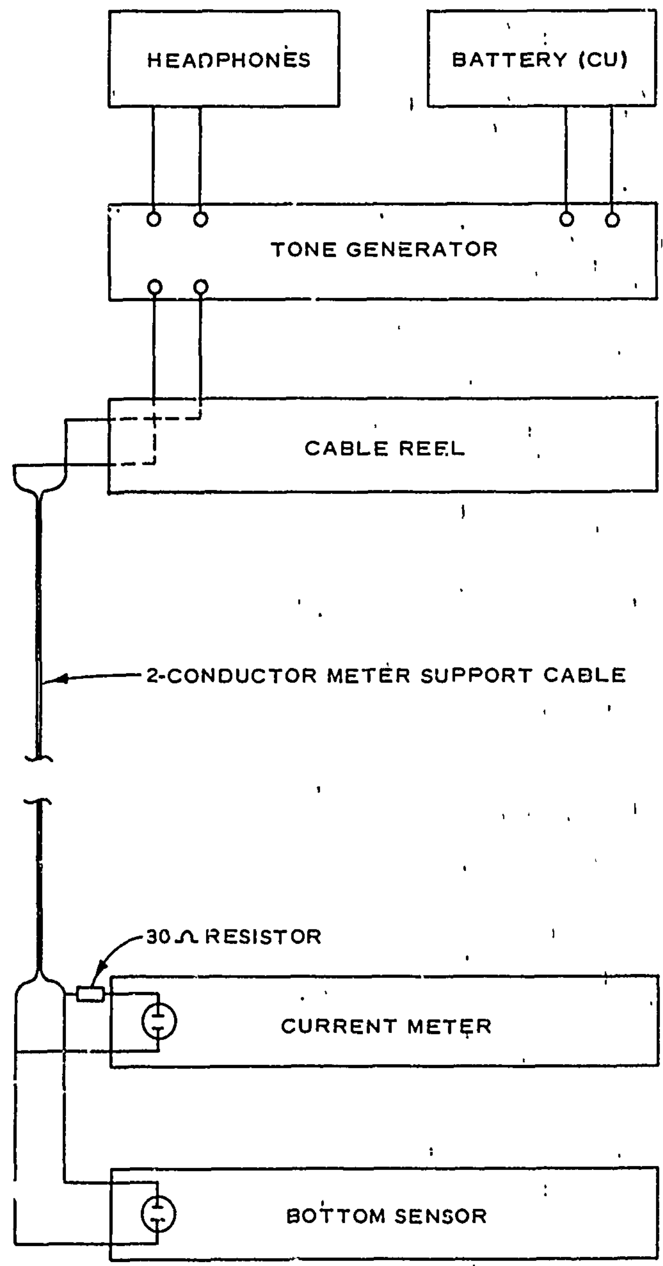


TONE GENERATOR



GENERATOR HOUSING

SCHEMATIC OF TONE GENERATOR
AND HOUSING



COMPONENT CONNECTIONS OF TONE GENERATOR

PLATE B8

APPENDIX C

DATA FROM SHOAL SAMPLE ANALYSES

FLOCCULATION TESTS

Bottom samples taken with modified Trask sampler at 4 locations in the [illegible] area. The top centimeter of material was removed from each sample and percent moisture content determined. A composite sample of about one pint was made up from bottom material obtained no deeper than one foot below the top of the shoal.

Location	Date (1968)	Moisture Content Percent A	B	C	D	E	F	Avg.	Composite Bottom Sample No.
131 South	20 Sep	84.6	84.8	84.0	80.9	85.2	84.9	84.1	1
128 North	20 Sep	80.6	79.8	80.9	83.1	76.8	78.6	80.0	2
125 South	20 Sep	92.8	88.1	88.0	88.4	88.0	86.9	88.7	3
122 South	19 Sep	82.7	84.2	84.0	84.7			83.9	4
131 South	1 Oct	83.3	-	82.7	84.2			83.4	5
128 North	1 Oct	80.6	78.9	82.3	-			80.6	6
125 South	1 Oct	86.3	86.0	86.1	86.3			86.2	7
122 North	1 Oct	84.7	84.9	85.5	84.6			84.9	8
131 South	11 Oct	84.9	82.3	83.9	83.7			83.7	9
128 North	11 Oct	90.0	86.5	83.5	81.7			85.4	10
125 South	11 Oct	86.5	84.6	87.6	86.7			86.4	11
122 North	11 Oct	82.6	82.8	84.5	83.9			83.5	12
131 South	22 Oct	81.7	82.5	83.2	80.9			82.1	13
128 North	22 Oct	83.6	87.4	81.2	84.7			84.2	14.
125 South	22 Oct	85.8	91.9	90.8	87.0			88.9	15
122 North	22 Oct	82.5	83.7	82.2	81.1			82.4	16

Note: One extra sample No. 3 at Sta 125 South - 20 Oct.

Corps of Engineers, USAE Waterways Experiment Station	Report on Physical, Chemical, and Petrographic Data	Concrete Division P. O. Drawer 2131 Jackson, Mississippi
Project Examination of 16 Samples from Shoals in Savannah, Georgia Harbor		Date 20 February 1969
Job No. 546-H377.19SE31		Initials: BA

Samples

1. Sixteen samples from shoals in Savannah Harbor, Georgia, were received for testing by the Soils Division of the U. S. Army Engineer Waterways Experiment Station (WES) in the fall of 1968. Each sample was a combination of sediment and water in a one-pint jar. The Soils Test Section divided the samples, keeping part of each for their tests and forwarding the balance of each (about 25 g) to the Concrete Division (CD) on 15 November 1968. The 16 samples are identified below by CD serial number and field number:

CD Serial No.	Field No.
WES-40 Ss-1 (A through D)	Sta 131 S - Samples 1, 5, 9, 13
WES-40 Ss-2 (A through D)	Sta 128 N - Samples 2, 6, 10, 14
WES-40 Ss-3 (A through D)	Sta 125 S - Samples 3, 7, 11, 15
WES-40 Ss-4 (A through D)	Sta 122 N - Samples 4, 8, 12, 16

Test Procedure

2. The Soils Test Section determined particle-size distribution and specific gravity for 14 samples, and weight loss on ignition at 800 C for 12 of the samples. There was insufficient material to do these tests for the other samples.

3. The CD determined total cation-exchange capacity (CEC) of each sample, made a petrographic examination of all samples, and measured the weight loss of four samples at 375 C as a measure of organic content.

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Rev. March 1964

4. The different tests are described in the following subparagraphs:

a. Particle-size distribution and ignition loss. The Soils Test Section determined the gradation and specific gravity of the samples in the as-received condition in accordance with provisions of Appendices IV and V of EM 1110-2-1906, dated 10 May 1965. The Soils Test Section also determined the loss on ignition as outlined in Methods of Analysis of the Association of Official Agricultural Chemists, 6th edition, 1945. That procedure consisted of processing the sample (wet) through a No. 10 U. S. standard sieve, heating approximately 2 grams (dry weight) of the material at 105 C for five hours, and then igniting the specimen at 800 C for one hour and calculating the weight loss.

b. Cation-exchange capacity. Each sample was air dried and passed through a No. 10 sieve. Cation-exchange capacity was then determined on each of the samples by replacing the native exchangeable cations with 1 N sodium acetate, removal of the excess sodium acetate with alcohol, replacement of the adsorbed sodium acetate with 1 N ammonium acetate, and determination of the replaced sodium.

c. Petrographic examination. The remainder of each air-dried sample was ground to pass a No. 325 sieve (44μ). The samples were then examined on an XRD-5 diffractometer using nickel-filtered

copper radiation at 27 kvcp and 41 ma or 50 kvcp and 21 ma at scanning speeds of 2 deg 2θ per minute or 0.2 deg 2θ per minute under the following conditions:

(1) Tightly packed powders.

(2) As a slurried slide of the material finer than No. 325 sieve, both air-dried and after glycerolation.

(3) Selected samples were examined as air-dried sedimented clay slides of minus 2μ material, and as sedimented slides heat-treated at 150 C, 300 C and 450 C.

d. Differential thermal analysis. Selected samples passing a No. 325 sieve were examined by differential thermal analysis (DTA) in a nitrogen atmosphere, using a heating rate of 10 C per minute.

e. Organic content. Keeling* has shown that ignition of clay samples at 375 C for 16 hours removes the carbonaceous materials in clays, without removing water contained in the structure of the clay, and without destroying either iron sulfides or carbonates which may be present. One sample from each station was ignited at 375 C for 16 hours and the loss in weight was determined.

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*Keeling, P. S., "Some Experiments on the Low-Temperature Removal of Carbonaceous Material from Clays," Clay Minerals Bulletin, Vol 5, No. 28, December 1962, pp 155-158.

f. Other examinations. Dilute hydrochloric acid and a magnetized needle were used to check for the presence of carbonate minerals and magnetic iron-bearing minerals respectively. Powder immersion mounts were examined with a petrographic microscope.

Results

5. Particle-size distribution curves for all samples except 4 and 6 are shown in figs. 1-14. All of the physical and chemical data obtained are reported on table 1. Samples 4 and 6 were too small to permit particle-size distribution, specific gravity, and loss on ignition at 800 C to be determined. Samples 13 and 15 were too small to permit loss on ignition at 800 C to be determined. The samples contain much more material finer than 2μ than most soils or sediments. The material finer than 2μ makes up 52 to 65 percent of each sample.

Station No.	Sample No.	Sampling Date	Cumulative % -- 2μ
131S	1	20 Sep 68	60
	5	1 Oct 68	65
	9	11 Oct 68	62
	13	22 Oct 68	60
Range for Station 131S			60 - 65
125S	3	20 Sep 68	58
	7	1 Oct 68	59
	11	11 Oct 68	59
	15	22 Oct 68	61
Range for Station 125S			58 - 61
122N	4	20 Sep 68	nd
	8	1 Oct 68	52
	12	11 Oct 68	57
	16	22 Oct 68	56
Range for Station 122N			52 - 57

(Continued)

Physical, Chemical, and
Petrographic Report (Continued) Date: 20 February 1969
Project: Examination of 16 Samples from Shoals in Savannah, Georgia, Harbor

Station No.	Sample No.	Sampling Date	Cumulative % -- 2μ
128N	2	20 Sep 68	60
	6	1 Oct 68	nd
	10	11 Oct 68	55
	14	22 Oct 68	57
Range for Station 128N			55 - 60

6. The compositions and relative proportions of minerals in all 16 samples are very similar. The representative composition and proportions are shown below:

Constituents	Relative Abundance
Clay Minerals	
Kaolin	Abundant
Clay-mica	Minor
Montmorillonite	Minor
Vermiculite	Minor
Nonclay Minerals	
Quartz	Minor
Plagioclase	Very Minor - Minor
Potassium feldspar	Very Minor - Minor
Halite	Minor
Pyrite	Minor
Cristobalite	Trace ?

Halite was found in the samples examined as air-dried powders and slurries, but not in sedimented slides prepared from dilute suspensions. Two minerals were identified which are characterized by basal spacings at about 14-A in the air-dry condition--montmorillonite and vermiculite. When sedimented slides were examined after glycerolation, basal spacings at about 14 A and 17 A were found, indicating the presence of a nonexpanding mineral with a 14-A spacing and the presence of an expanding montmorillonitic clay forming a complex with glycerol. The two minerals contributing to the 14-A

spacing in air-dried sedimented slides collapsed partially after heat treatment at 150 C, leaving a barely perceptible hump in the 6 to 7 2θ region (14.7 to 12.6 A) which was not present in slides heat treated at 300 C or 450 C.

7. Several workers have reported poorly crystallized vaguely characterized clay minerals from estuaries on the Atlantic Coast of the southeastern United States;* they may differ from river to river depending on local differences in material eroded. They have been referred to as chlorite-vermiculite and as vermiculite. The preponderant evidence obtained on this group of samples indicates that vermiculite is present. It cannot be unequivocally demonstrated that interlayered chlorite-vermiculite, or chlorite, is absent. Neiheisel and Weaver did not report vermiculite from Savannah Harbor.

8. Diatom fragments were observed by microscope in most samples and are undoubtedly present in all. They are probably the source of the cristobalite that is believed to be present.

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* Powers, M. C., "Adjustment of Clays to Chemical Change and the Concept of Equivalence Level," Clays and Clay Minerals, Proc., Sixth National Conference on Clays and Clay Minerals, 1957, p 309, Ada Swineford, Editor, Pergamon Press, 1959.

Nelson, B. W., "Clay Mineralogy of the Bottom Sediments, Rappahannock River, Virginia," Clays and Clay Minerals, Proceedings, Seventh National Conference on Clays and Clay Minerals, 1958, A. Swineford, Editor, Pergamon Press, 1960, p 135.

Neiheisel, J., and Weaver, C. E., "Transport and Deposition of Clay Minerals, Southeastern United States," Journal of Sedimentary Petrology, Vol 37, No. 4, pp 1084-1116, December 1967.

9. The loss on ignition of samples fired at 800 C for one hour ranged from 13.9 to 17.7 percent, while the loss on ignition of samples fired at 375 C for 16 hours ranged from 9.0 to 9.7 percent. Presumably the losses at 800 C include the hydroxyl in the structures of the clays and may include results of breakdown of very minor quantities of sulfides and carbonates in the samples. Kaolin, the major clay mineral in all the samples, is not stable above 550 - 600 C and loses four (OH). The loss in weight of the samples ignited at 375 C is believed to be a good measure of the organic content in the samples.

10. The clay minerals present in all samples were poorly crystalline. The nonclay minerals were present as very fine particles with over 90 percent passing a No. 200 sieve. Under the microscope the sample appears to be over 80 percent clay while the X-ray pattern appears to show that clay is present in an amount less than 20 percent. This inconsistency is somewhat explained by a high background level on the X-ray patterns and the obviously poor crystallinity of the clay minerals present. Clay minerals are believed to amount to more than half of each sample.

11. The sixteen samples from shoals in Savannah Harbor are of similar mineral composition, consisting of the clay minerals kaolin, clay mica, montmorillonite, and vermiculite, and of the nonclay minerals quartz, plagioclase and potassium feldspar, pyrite, halite (from the estuarine water), and possibly cristobalite. All of the samples were very fine grained with over 50 percent finer than 2μ. Cation-exchange capacity ranged in single determinations from 30.4 to 43.3 meq per 100 g; the highest average value was that for station 122N, 38.9, but the highest individual value was determined in sample 6 from station 128N.

12. We did not find a relation between any pair or group of properties determined for this group of samples when the samples were sorted either by stations or by sampling days.* It is possible that trends would become apparent if either samples from more stations or samples taken on more days, or both, were available.

13. The mineral composition is reasonable considering the geology of the source area and previous published results on samples from the Savannah River (ref 3, p 6).

* Samples 1, 2, 3, 4(?) were taken 20 Sep 68; samples 5, 6?, 7, 8, 1 Oct 68; samples 9, 10, 11, 12, 11 Oct 68; samples 13, 14, 15, 16, 22 Oct 68.

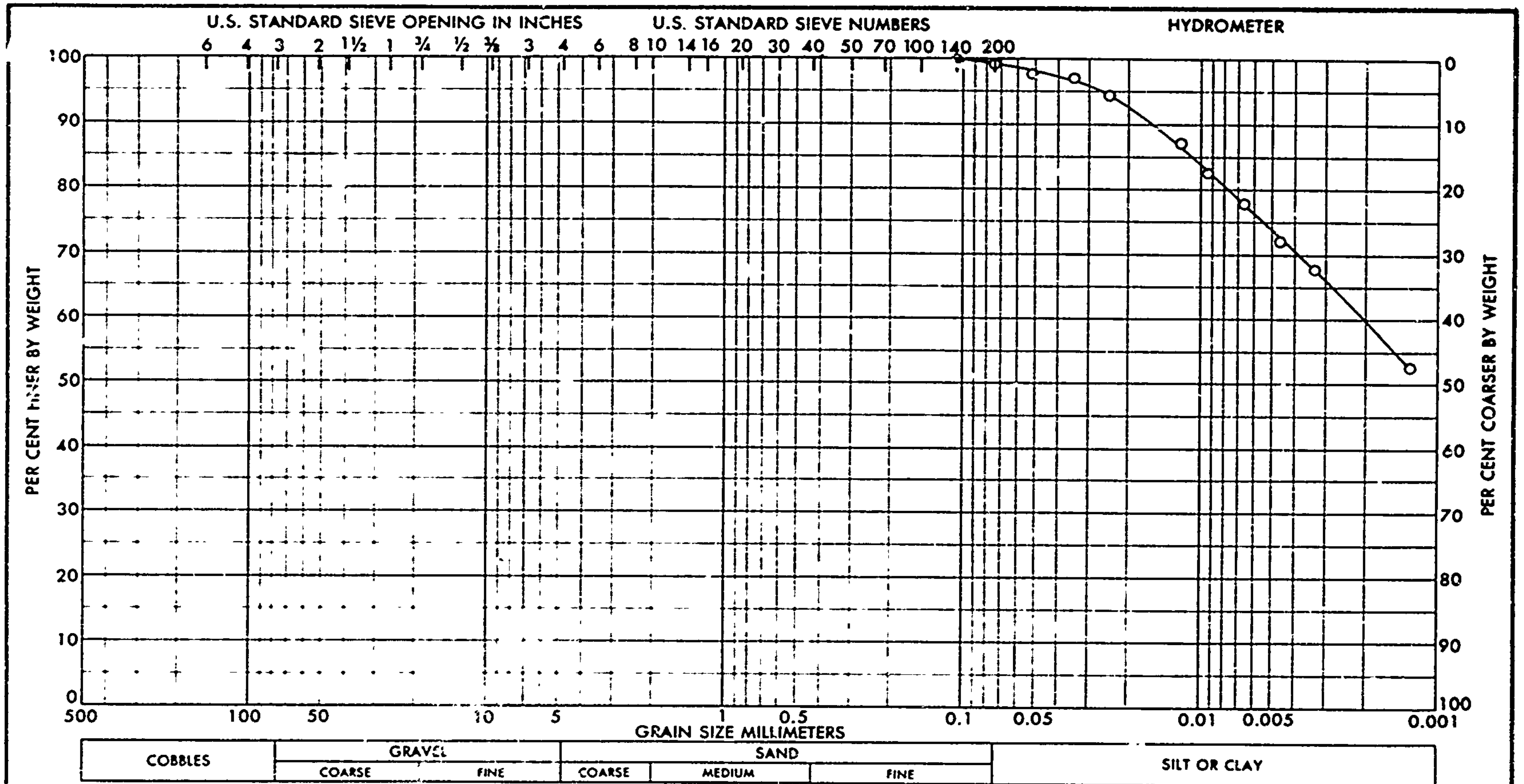
15 Incl
Table 1
Figs. 1-14

Table 1

Physical Data on 16 Shoal Samples from Savannah Harbor

Field Identification Station No.	Field Identification Sample No.	Specific Gravity G_s	Cation-Exchange Capacity Milliequivalents/100 g Sample	Cation-Exchange Capacity Milliequivalents/100 g Avg for Shoal	% Wt Loss on Ignition at 800 C	% Organic Content (wt loss at 375 C)
131 S	1	2.60	35.2)		16.4	9.1
	5	2.53	39.6)	36.4	16.6	
	9	2.57	32.4)		15.5	
	13	2.58	38.2)		n.d.[a]	
Range		2.53 - 2.60	32.4 - 39.6		15.5 - 16.6	
128 N	2	2.53	35.9)		15.4	9.0
	6	n.d.	43.3)	36.2	n.d.	
	10	2.58	33.5)		13.9	
	14	2.62	32.0)		16.4	
Range		2.53 - 2.62	32.0 - 43.3		13.9 - 16.4	
125 S	3	2.54	38.3)		17.7	9.4
	7	2.52	30.4)	36.9	16.6	
	11	2.60	40.0)		15.7	
	15	2.63	38.8)		n.d.	
Range		2.52 - 2.63	30.4 - 40.0		15.7 - 17.7	
122 N[b]	4	n.d.	42.3)		n.d.	9.7
	8	2.53	38.0)	38.9	15.1	
	12	2.56	37.6)		16.3	
	16	2.53	37.6)		14.8	
Range		2.53 - 2.56	37.6 - 42.3		14.8 - 16.3	

(a) Not determined.
(b) It is possible that sample 4 was taken on the south side of the river and samples 8, 12, and 16 on the north.

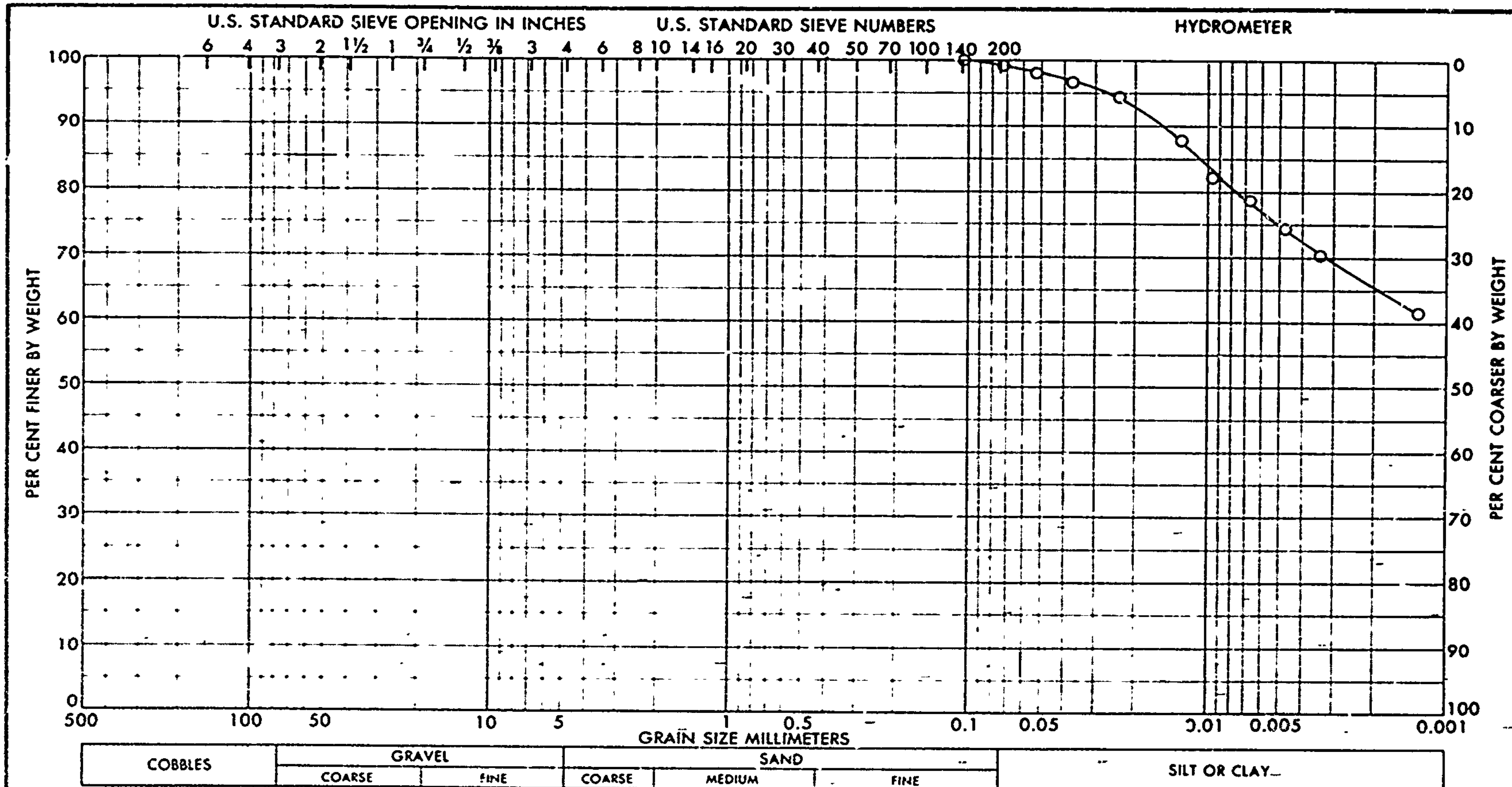


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1		Gs= 2.60				
		Loss on Ignition= 16.4%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 131 South (20 Sept. 68)

Date: 17 JANUARY 1969

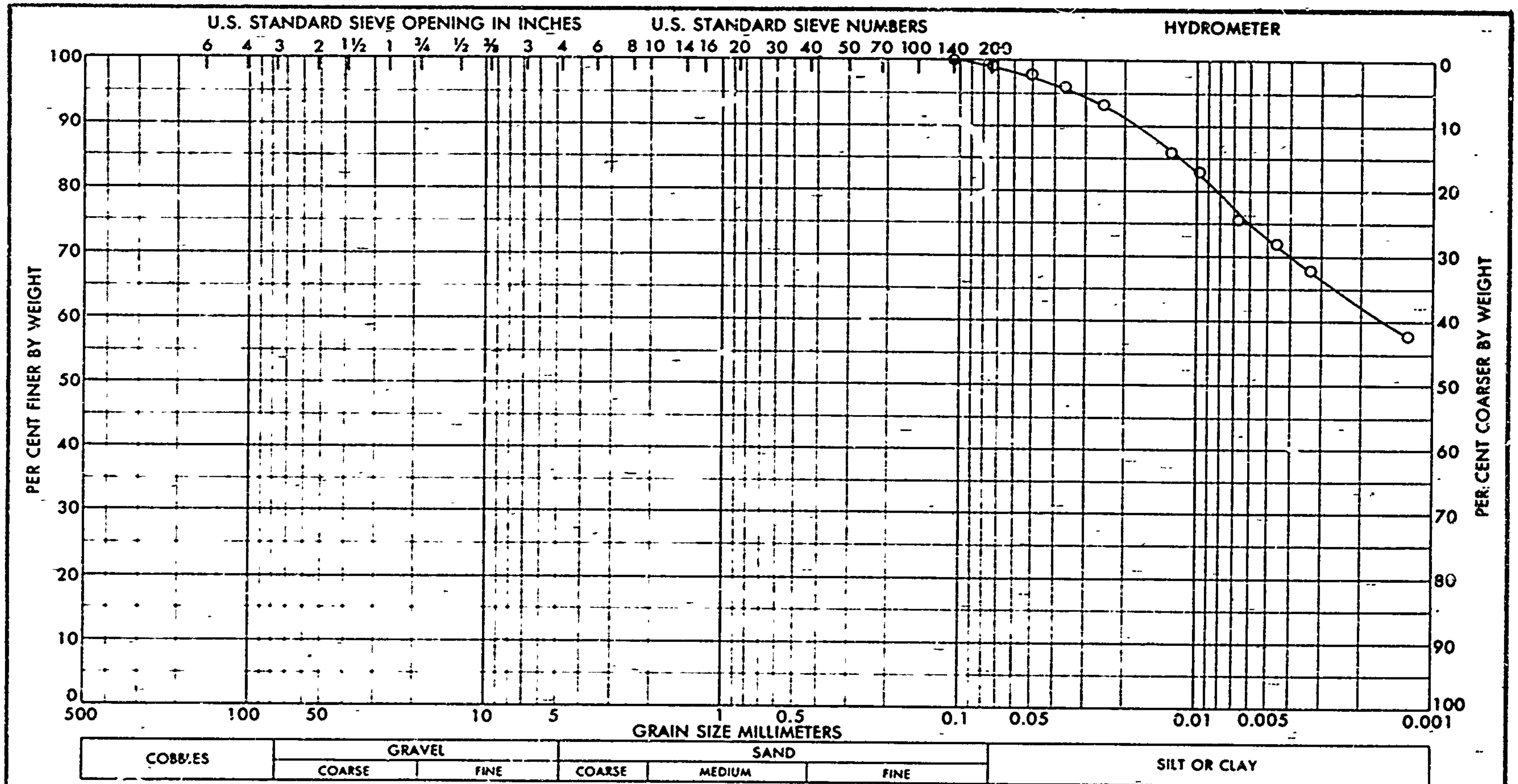


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
5		Gs= 2.53				
		Loss on ignition= 16.6%				

Project: SAVANNAH HARBOR FLOC-CULATION STUDY

Area: 131 South (1 Oct. 68)

Date: 17 JANUARY 1969

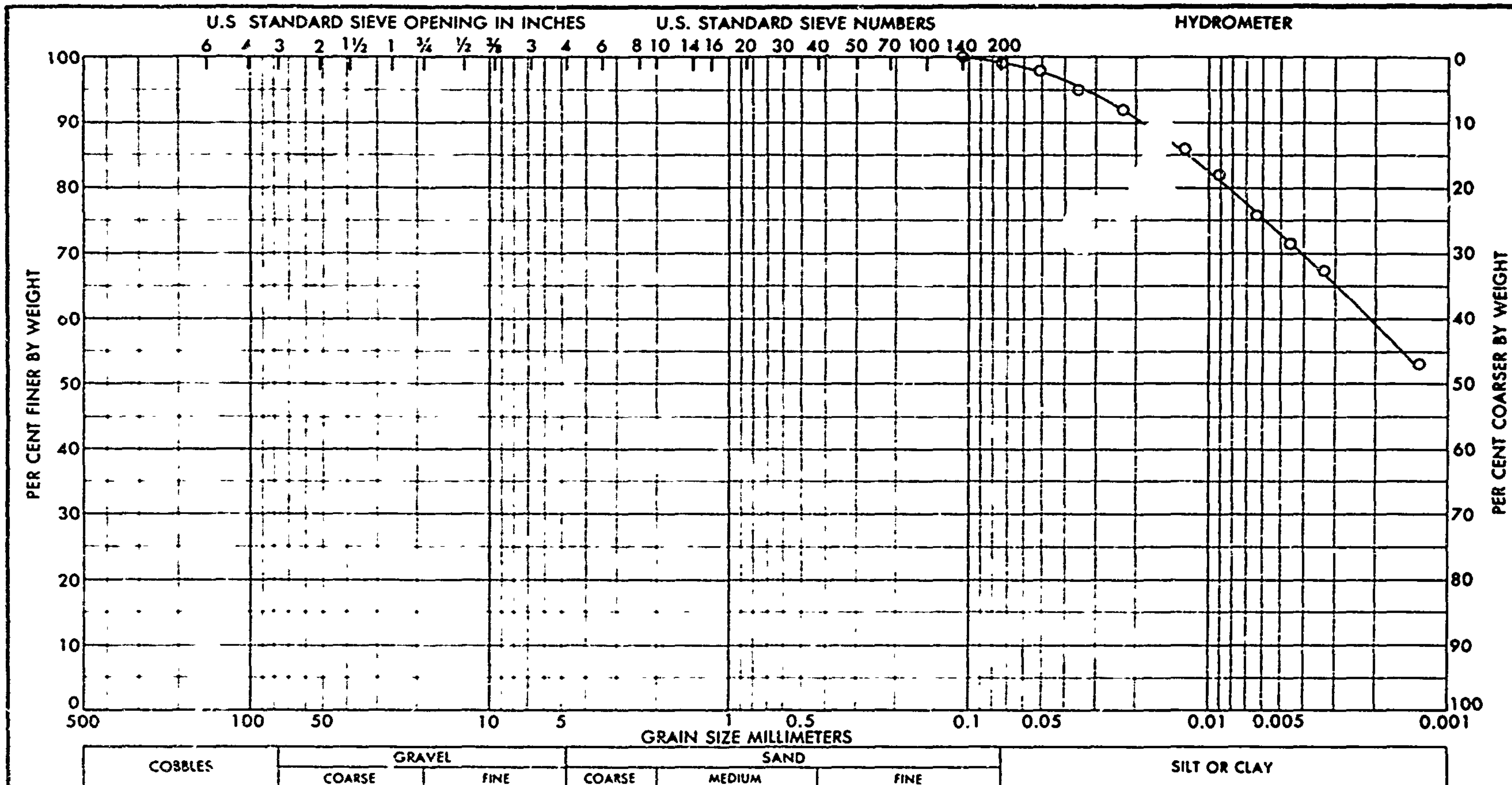


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
		Gs= 2.57				
		Loss on Ignition= 15.5%				

Project: SAVANNAH HARBOR FLOC-CULATION STUDY

Area: 13 South (11 Oct. 68)

Date: 17 JAN. 1969

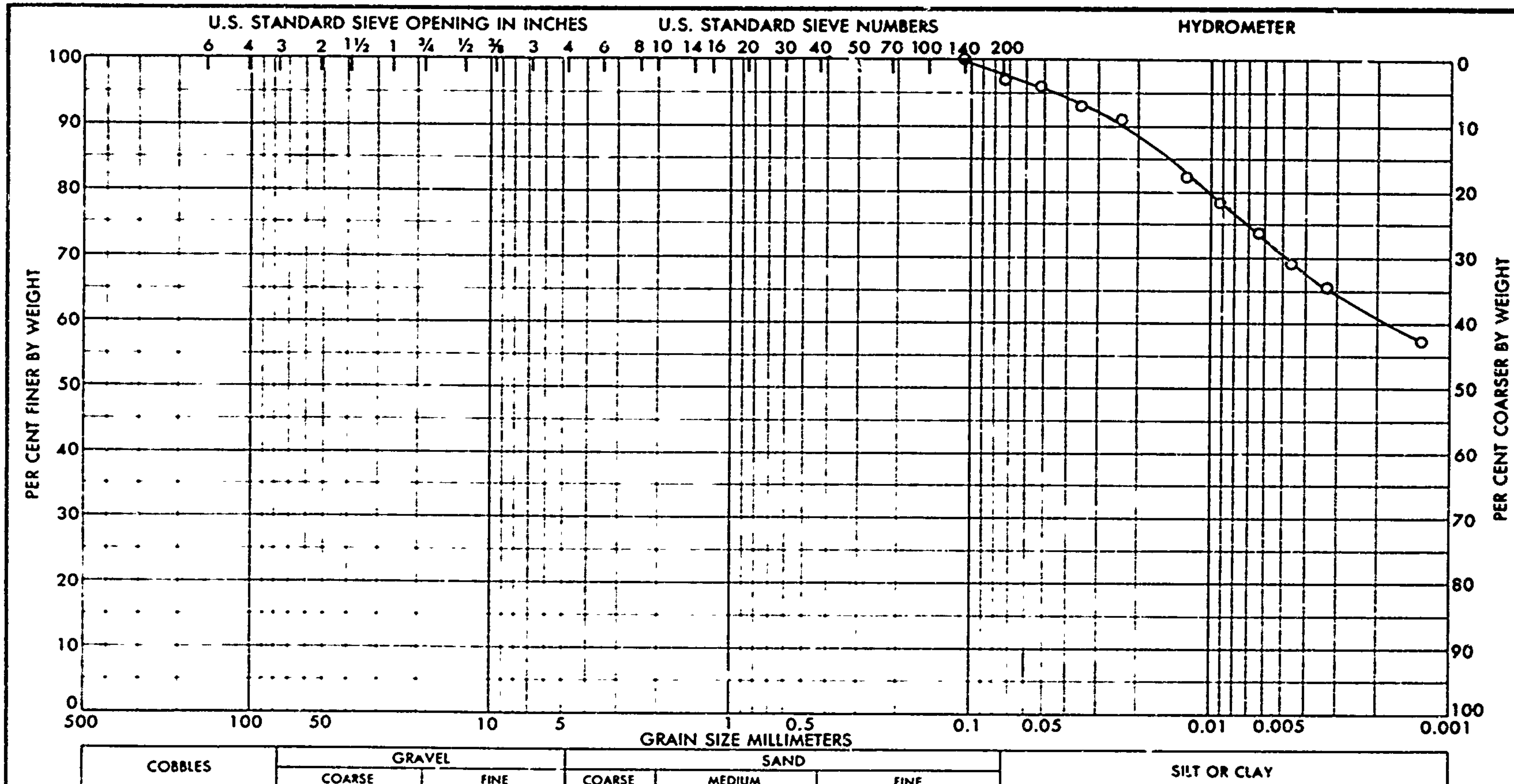


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
13		Gs= 2.58				
		Insufficient material for				
		Loss on Ignition test				

Project: SAVANNAH HARBOR FLOC-CULATION STUDY

Area: 131 South (22 Oct. 68)

Date: 17 JANUARY 1969

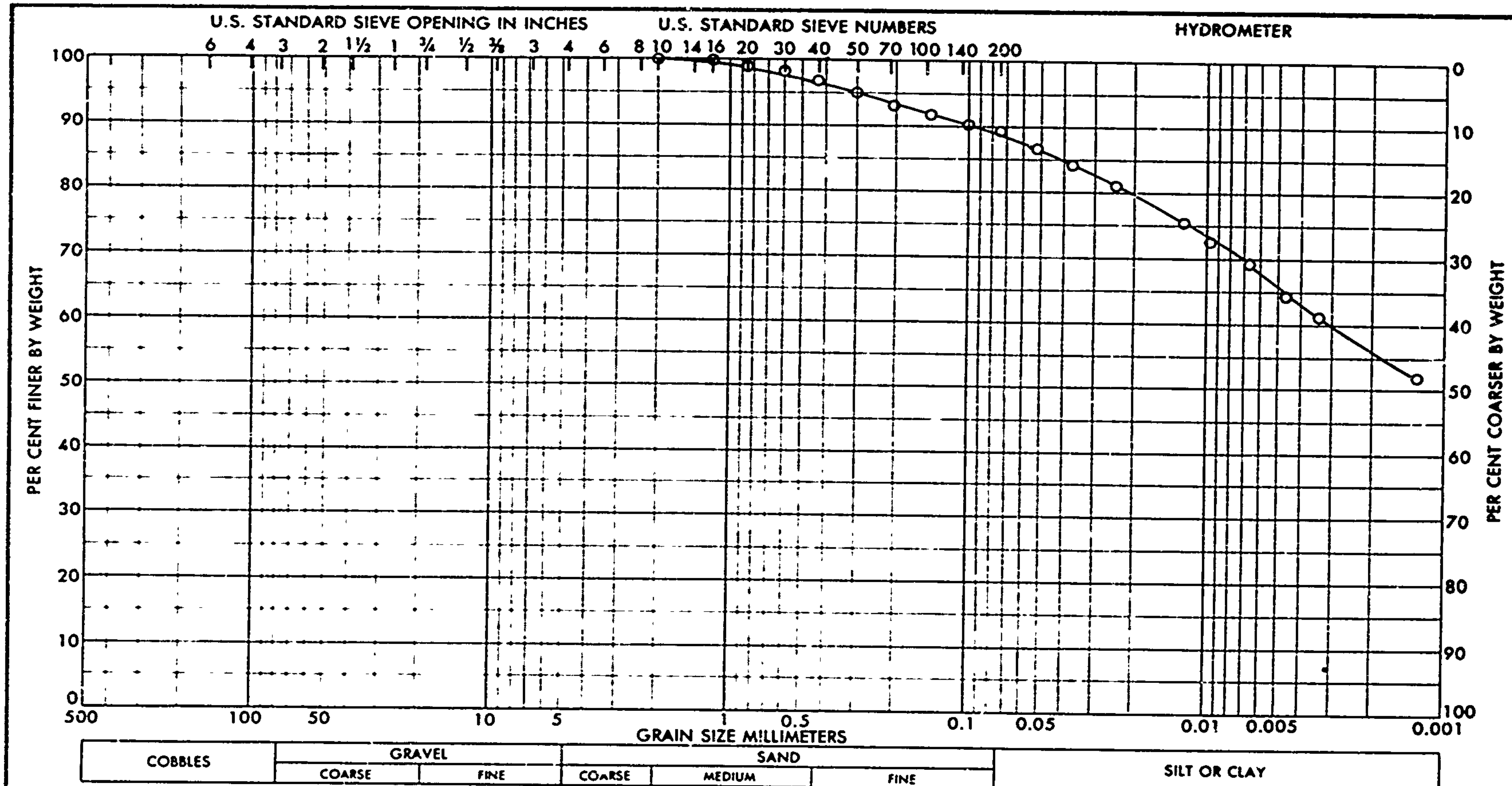


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
2		Gs= 2.53				
		Loss on Ignition= 15.4%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 128 North (20 Sept. 68)

Date: 17 JANUARY 1969

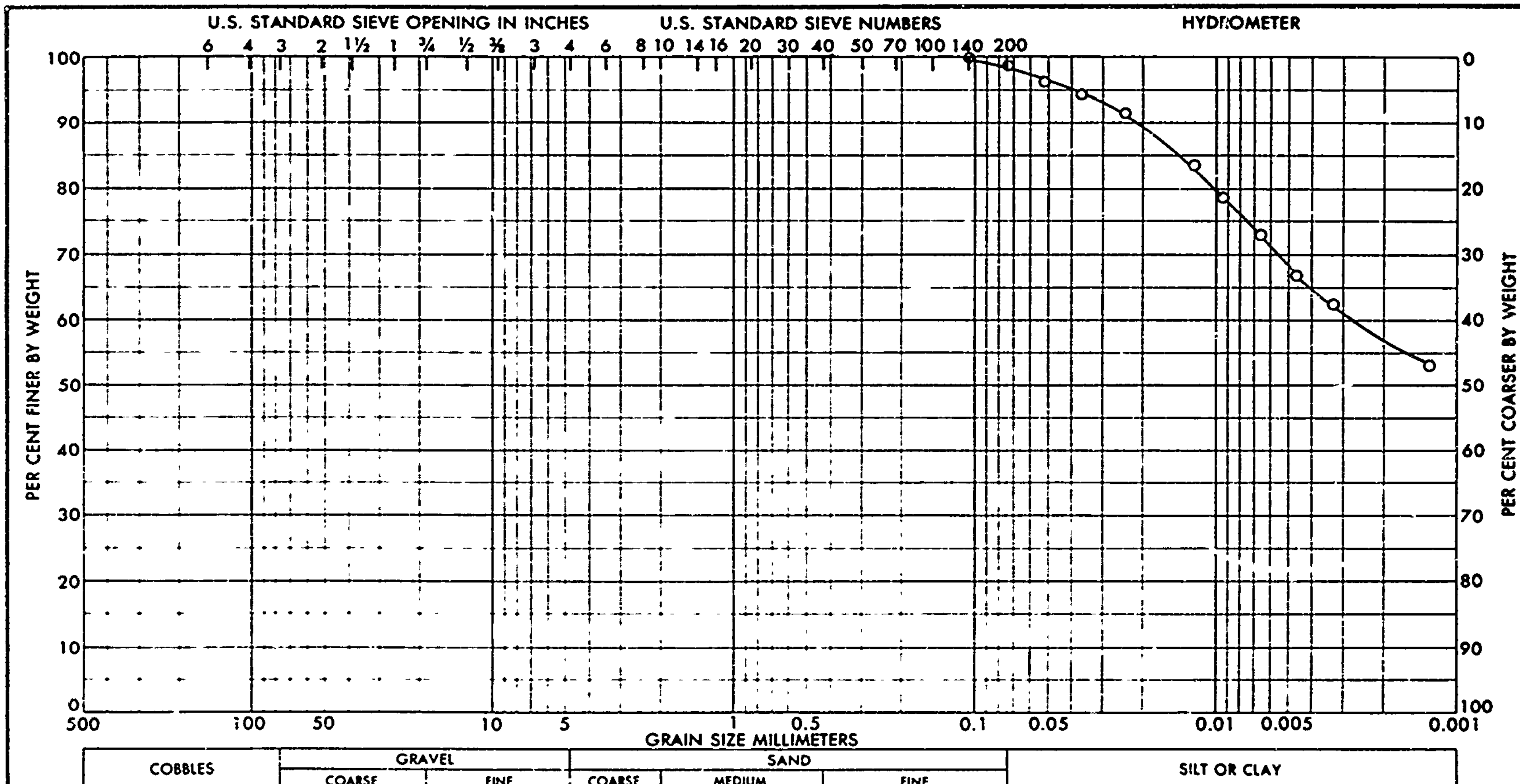


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
10		Gs= 2.58				
		Loss on Ignition= 13.9%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 128 North (11 Oct. 68)

Date: 17 JANUARY 1969

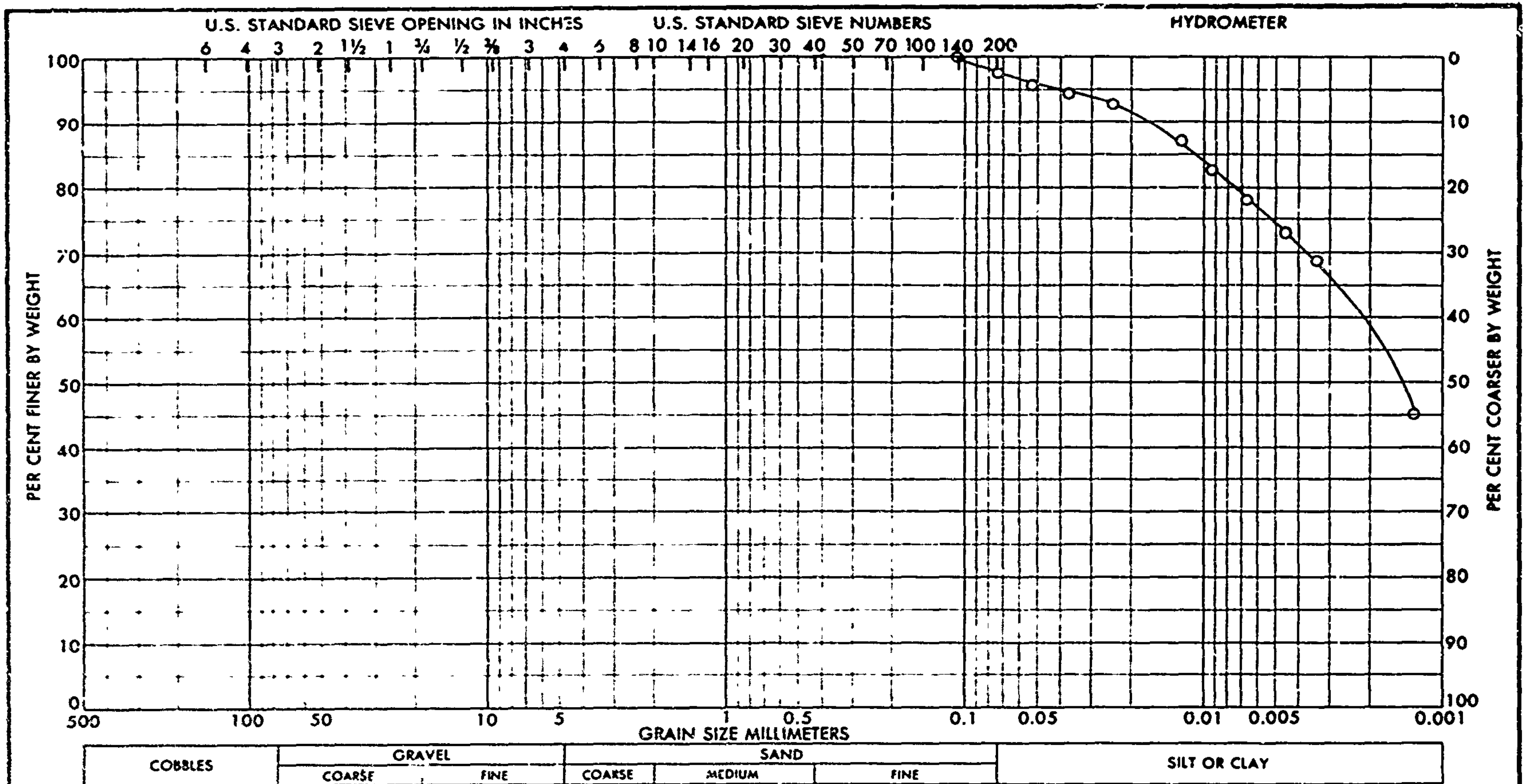


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
14		Gs= 2.62				
		Loss on Ignition= 16.4%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 128 North (22 Oct. 68)

Date: 17 JANUARY 1969

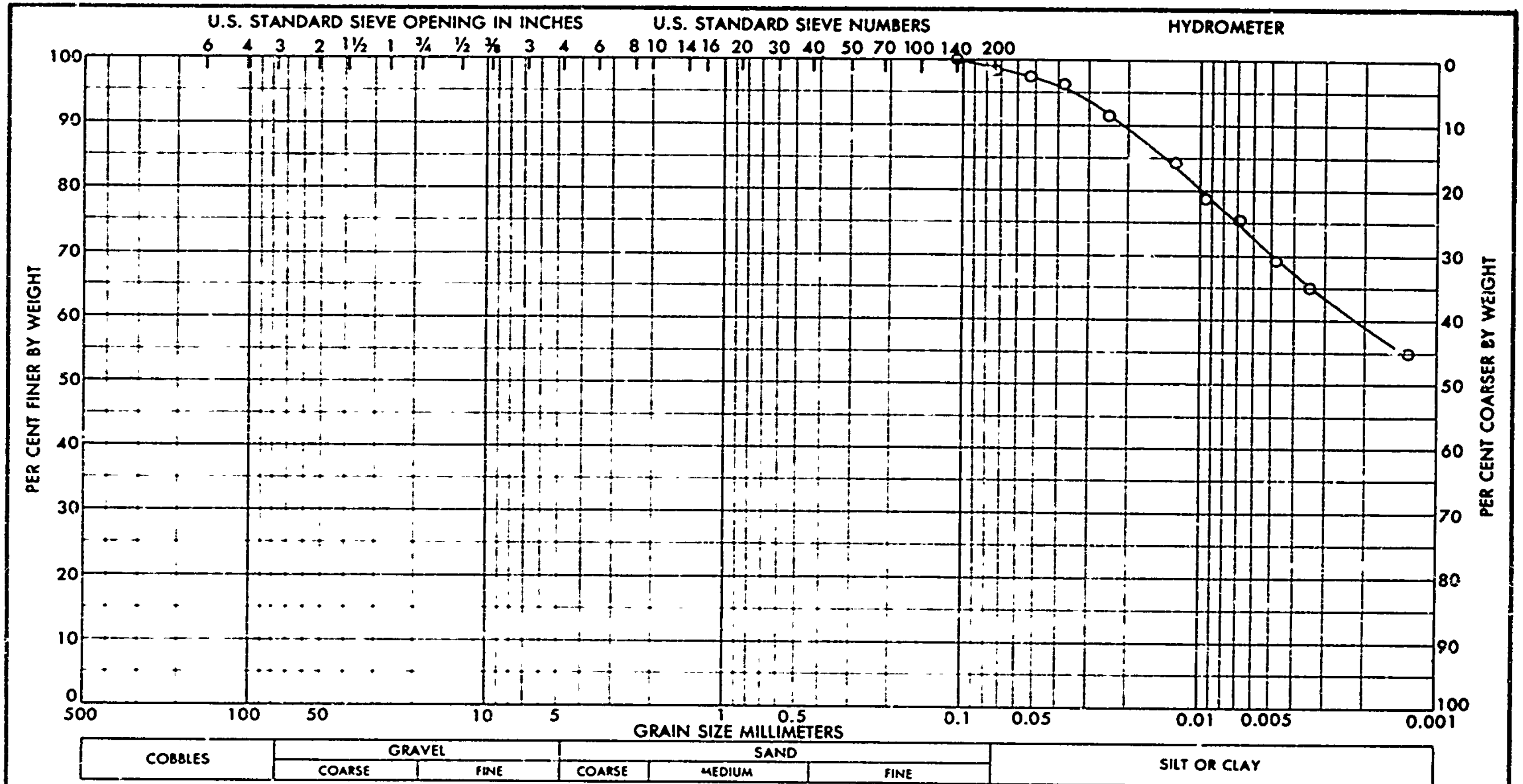


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
3		Gs: 2.54				
		Loss on Ignition= 17.7%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 125 South (20 Sept. 68)

Date: 17 JANUARY 1969

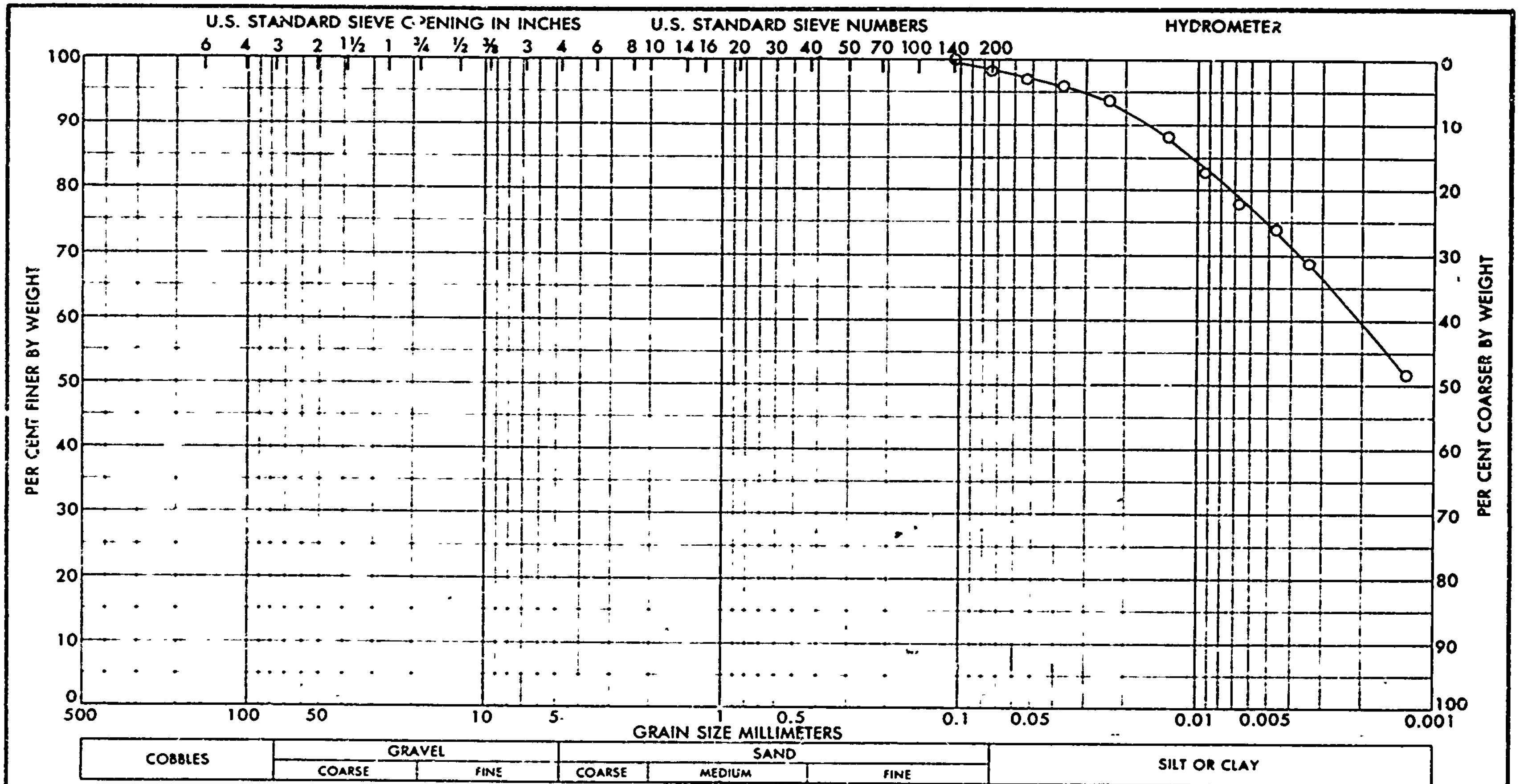


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
7		Gs= 2.52				
		Loss on Igrition= 16.6%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 125 South (1 Oct. 68)

Date: 17 JANUARY 1969

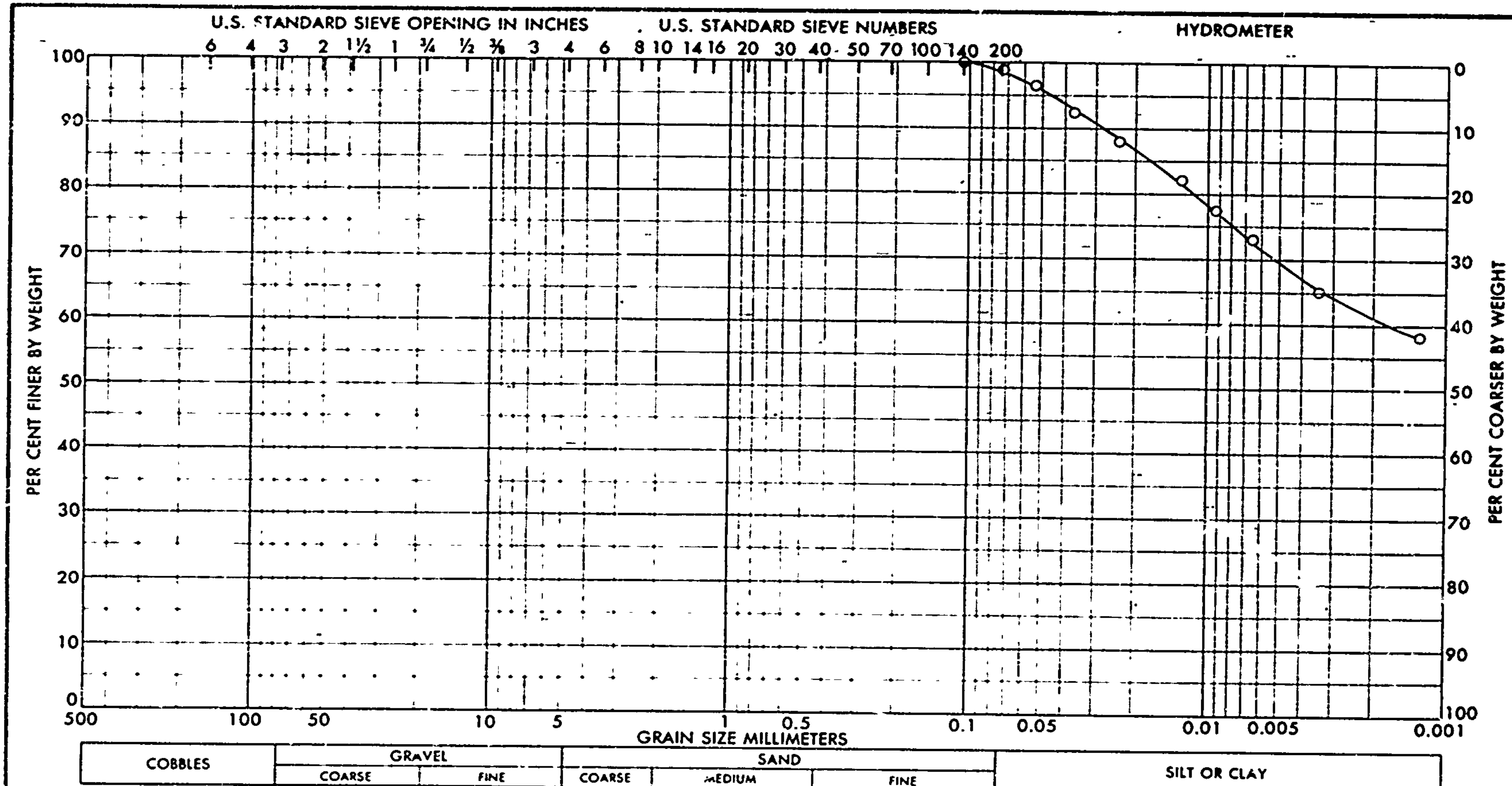


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
11		Gs= 2.60				
		Loss on Ignition= 15.7%				

Project: SAVANNAH HARBOR FLOC- CULATION STUDY

Area: 125 South (11 Oct. 68)

Date: 17 JANUARY 1969

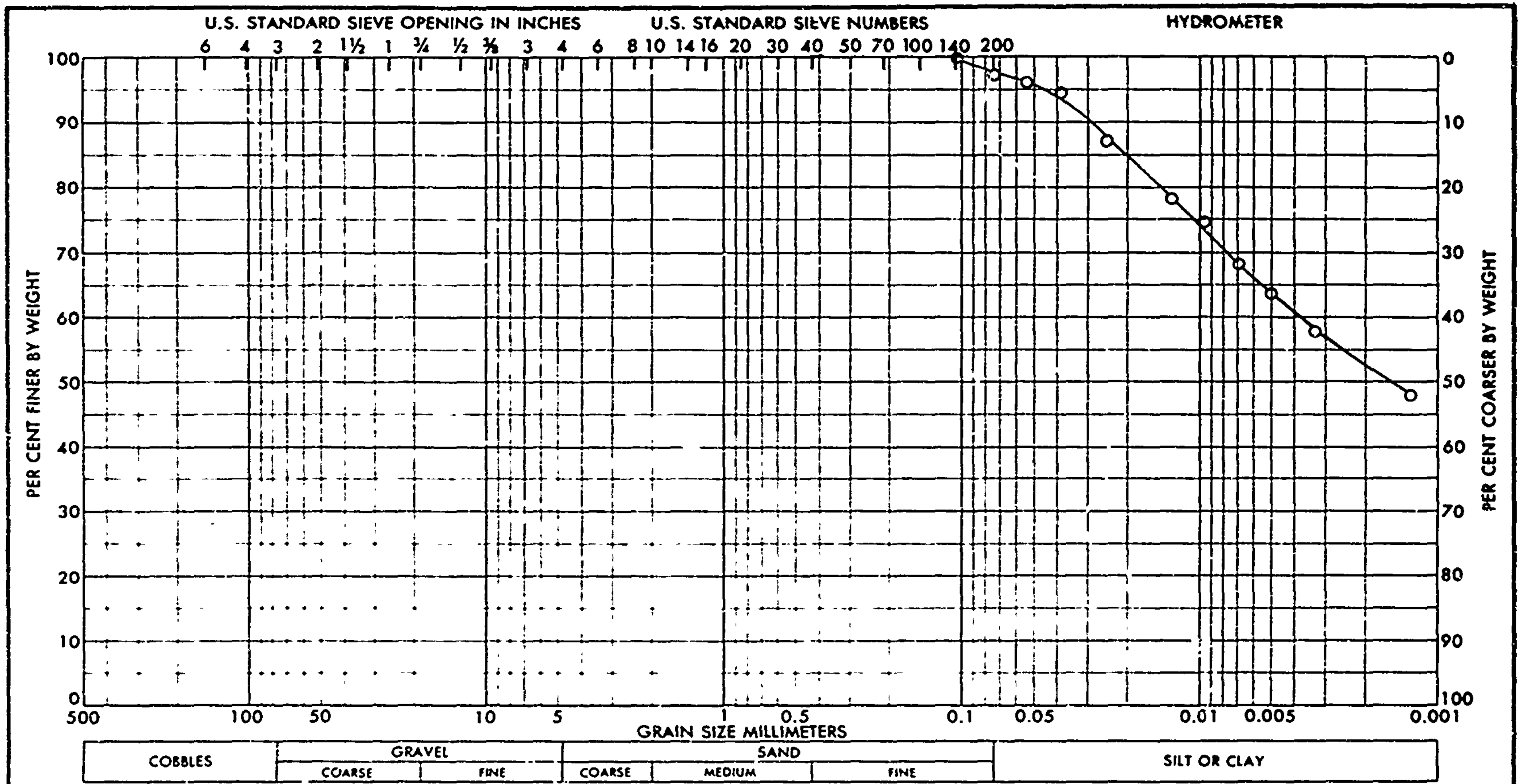


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
15		Gs= 2.63				
		Insufficient material for				
		Loss on Ignition test				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 125 South (22 Oct. 68)

Date: 17 JANUARY 1969

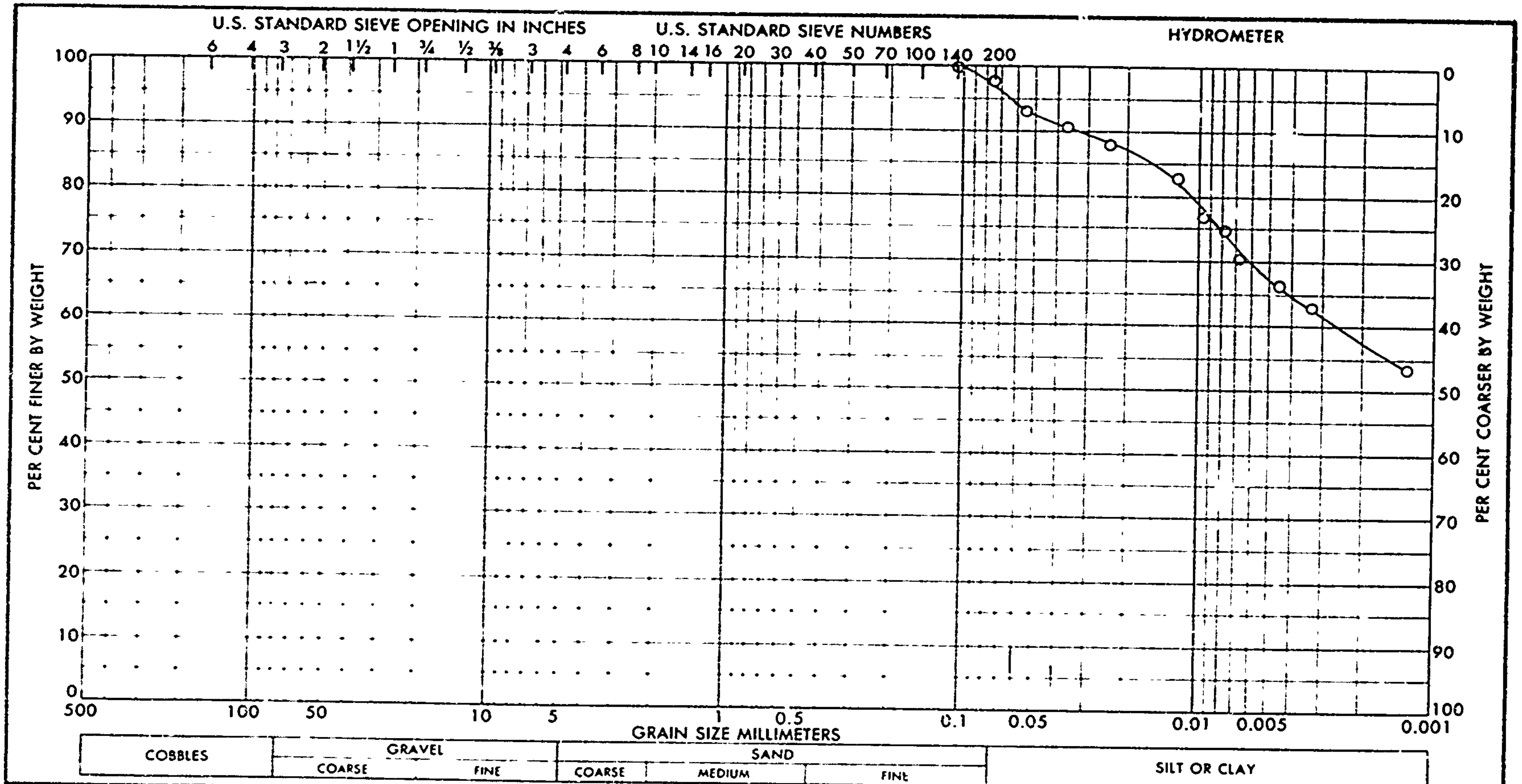


SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
8		Gs= 2.53				
		Loss on Ignition= 15.1%				

Project: SAVANNAH HARBOR FLOCCULATION STUDY

Area: 122 North (1 Oct. 68)

Date: 17 JANUARY 1969



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
12		Gs= 2.7				
		Loss on ignition= 16.3%				

Project: SAVANNAH HARBOR FLOC-CULATION STUDY

Area: 122 North (11 Oct. 68)

Date: 17 JANUARY 1969

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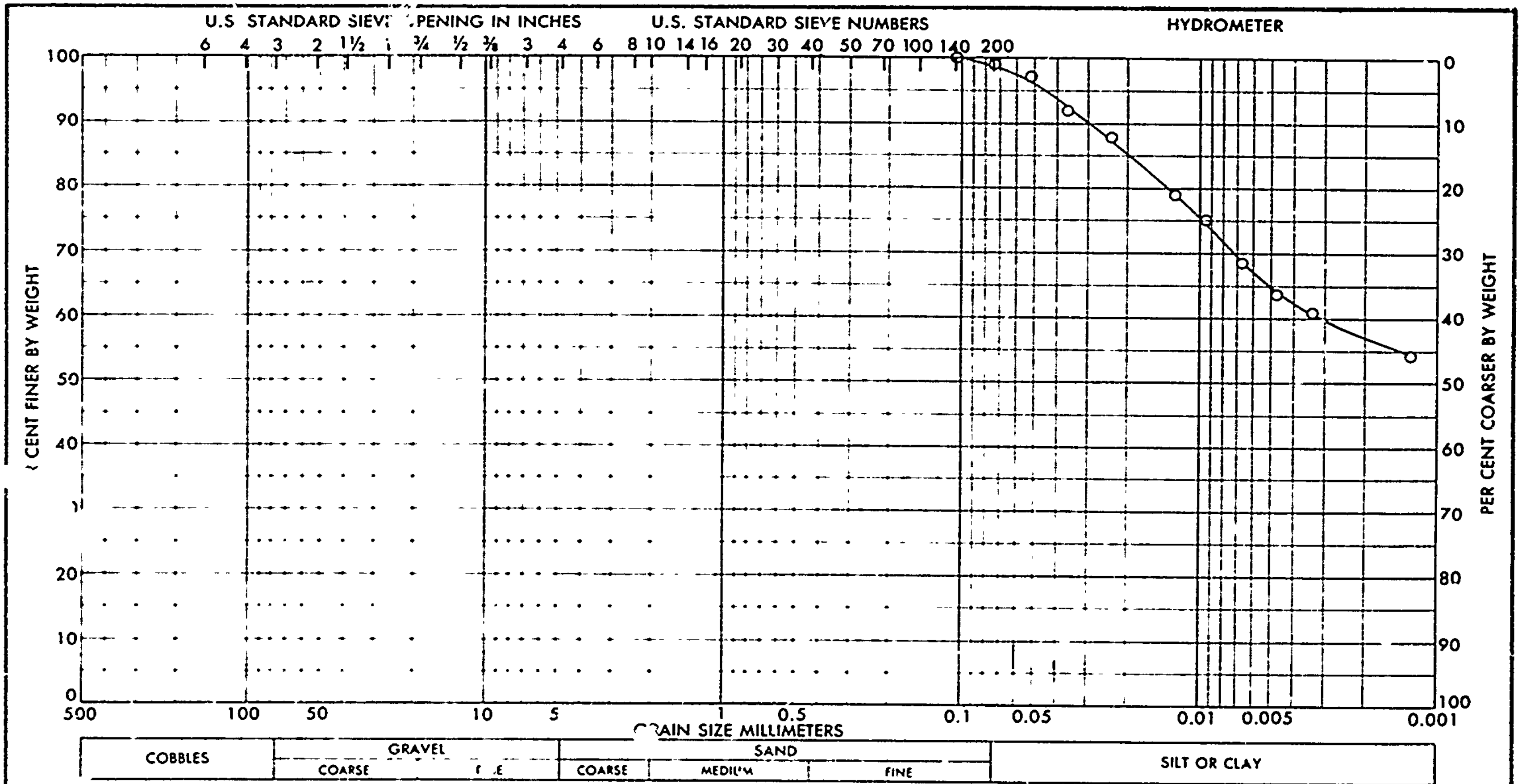

SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1		Gs= 2.73				
		Loss on Ignition= 14.8%				

Project: SAVANNAH HARFOR FLOC-CULATION STUDY

Area: 122 North (22 Oct. 68)

Date: 17 JANUARY 1969